Solar Panel Performance Optimization Through Robot-Assisted Cleaning and Monitoring

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***Abstract*—This project presents the design, development, and implementation of an IoT-enabled, autonomous robot dedicated to maintaining the efficiency of solar photovoltaic (PV) panels. The core objective is to mitigate the significant energy loss caused by the accumulation of dust, debris, and bird droppings, which often necessitates costly, hazardous, and inefficient manual cleaning. The robot is built around an Arduino UNO microcontroller, serving as the central processing unit that coordinates all functionalities. Its primary cleaning mechanism consists of a mopping motor for scrubbing and a water pump for rinsing the panel surface. For operational autonomy, the robot incorporates a small onboard solar panel to recharge its battery, with a voltage sensor continuously monitoring power levels. A defining feature of this system is its bidirectional Bluetooth communication with a custom mobile application. This allows for manual control and, crucially, real-time monitoring of environmental parameters-specifically temperature and humidity, measured by a DHT11 sensor. Furthermore, the system includes a security function: a PIR motion sensor, activated remotely via the application, to detect the presence of birds. Upon detection, an alert is sent to the user interface and an onboard buzzer is activated to deter the birds. This integrated approach offers a comprehensive, remote-operated solution for maintaining solar panel hygiene and ensuring.**

***Index Terms*—Robotic Controller, Solar cleaning process, Bluetooth communication, Sustainability, Efficiency, power**

I. INTRODUCTION

The global energy landscape is undergoing a profound transformation, with a decisive shift towards renewable sources to meet growing demand and address environmental concerns. Solar photovoltaic (PV technology has emerged as a cornerstone of this transition, offering a clean and sustainable method of electricity generation. However, the operational efficiency and economic viability of solar installations are critically dependent on environmental factors and maintenance practices. A significant challenge faced by solar panel owners is the inevitable accumulation of dust, pollen, bird droppings, and other debris on the panel surface [1]. This layer of soiling obstructs sunlight, leading to a substantial decrease in light transmittance and a corresponding drop in energy output losses that can easily exceed 15-20% if left unaddressed [2].

Traditional cleaning methods primarily involve manual labour using water hoses, brushes, or manual wiping [3]. These approaches are not only inefficient and time-consuming for large-scale installations, like solar farms or rooftop arrays, but also pose significant safety risks to personnel and potential for panel damage [4]. Furthermore, they consume large volumes of water, which is a scarce resource in many sun-rich regions. The frequency of required cleaning adds considerable operational and maintenance costs over the system's lifetime, undermining the economic benefits of solar power [5]. It features an onboard mechanism for dry and wet cleaning, autonomous recharging via a supplemental solar panel, and a suite of sensors to provide the panels' solar absorption capabilities and energy output. This innovation also reduces maintenance costs by prolonging the operational lifespan of solar installations.

Fig. 1. Prototype Image of Solar Panel Cleaning Robot

The intelligent monitoring system, equipped with advanced sensors, plays a crucial role in this approach by continuously assessing the condition of solar panels and monitoring environmental factors [6]. The sensor data facilitates adaptive cleaning schedules, optimizing the cleaning process based on real-time dust accumulation and weather conditions. This results in reduced water usage and operational expenses while maintaining the performance of solar panels [7]. By integrating these technologies, the proposed system becomes more focused on adapting sustainable energy practices. It not only ensures efficient and reliable solar energy production but also aligns with environmental conservation goals. This approach addresses current energy demands and supports the transition toward a cleaner and more sustainable future.

1. To Design and Fabricate a Functional Robotic Chassis.
2. To Develop a Bluetooth-Based Control and Monitoring System.
3. To Achieve Power Autonomy and Management.

II. LITERATURE REVIEW

In recent years, solar photovoltaic (PV) technology has gained significant attention as a major source of renewable energy, converting solar radiation directly into electricity [8]. Dust and dirt on PV modules or mirrors reduce power output by blocking sunlight. Over time, the efficiency of solar panels also drops due to factors like fallen leaves and water patches. To tackle this, various cleaning strategies are used, such as wet or dry cleaning, automatic or manual cleaning, different brushes or fabrics, and chemical additives. Additionally, natural cleaning methods like wind and rain are employed, especially in dry and semi-arid climates. Furthermore, research is ongoing to develop anti- soiling coatings [9]. Most of the solar panels are installed on top of the residential building roof tops. To reach and clean the solar panel is difficult. Because the roof of the house is best to install the solar panel it did not get any kind of shadow and should not block the sun rays. It is difficult in cleaning of dust particles and reduces efficiency of the solar panel. The area of the sun light falling place should not have covered and it is cleaned [10].

As mentioned earlier bird’s droppings, dust, high temperature, dirt this several actors can affect the PV panel efficiency [11]. The equipment for cleaning the solar panel must be made so as not to damage the solar panel surface, because if the surface is scratched, the sun's need to reach the surface and generate electricity will be reduced, which will cause a decrease in the efficiency of the solar panel. There are many types of surface cleaning materials to reduce the possibility of scratching. If the glass surface needs to be cleaned first, let the cleaning tools (brushes, wipers) clean the glass surface. If the surface of the glass is dry, continuing to clean with a cloth will cause friction between the two objects, which will cause the objects (dust, dirt or stones) between the glass and the wipe to wear away the glass, forming streaks.

The solar panel cleaning machine using the brush can get 73% of the dust [12]. The above mention designs can clean the solar panel automatically with the time based. It can use only for one panel, and we cannot know the output voltage of PV panel. To overcome this problem, by using the Bluetooth based control robot can use multiple panels one after one and also monitor the output voltage all the day which is generated by the solar panel in the LCD display.

III. PROPOSED SYSTEM

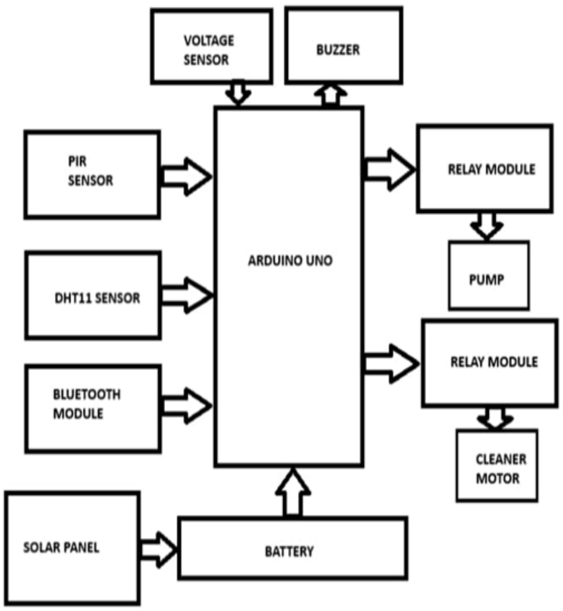

Fig. 2. Block diagram of the proposed system

The architecture of the solar panel cleaning robot is built upon the Arduino UNO as the central processing unit, integrating a comprehensive suite of sensors and communication modules to facilitate its core functionalities. The input and sensing subsystem provides all the necessary data for operation and monitoring [13]. Environmental conditions are captured by the DHT11 Sensor (temperature and humidity), while the PIR Sensor detects motion, primarily for the "Security Mode" to identify potential threats like birds. For essential power management, the Voltage Sensor continuously monitors the charge status of the Battery, which is passively replenished by the Solar Panel [14]. Crucially, the Bluetooth Module acts as the external interface, enabling bidirectional communication: it receives user commands (like "Clean" or "Activate Security Mode") from a custom mobile application and transmits all real-time sensor and battery data back to the user [15].

The Arduino UNO is the brain of the operation, executing the programmed state-machine logic to manage all concurrent tasks. It constantly processes the data streams from the sensors and interprets commands from the Bluetooth module [16]. This processing unit is responsible for decision-making, such as: initiating movement and cleaning upon a user command; continuously packaging and sending battery, temperature, and humidity data; and, critically, implementing the deterrent mechanism in "Security Mode [17]." If the PIR sensor signals a detection, the Arduino immediately triggers the buzzer and simultaneously sends an alert notification via the Bluetooth Module to the user's smartphone, completing the autonomous threat-response loop [18].

Finally, the output and actuation subsystem carries out the physical tasks dictated by the Arduino. The core cleaning functions-spraying water and scrubbing-are driven by the Pump and the Cleaner Motor, respectively. These high-power devices are interfaced with the low-power Arduino via Relay Modules, which are essential electrical switches that ensure the microcontroller is protected from the high current draw of the motors [19]. The system also includes a simple output device, the Buzzer, which is a direct, immediate, non-contact deterrent. This structured division into sensing, processing, and actuation modules, all centered around the Arduino, ensures a reliable and functional closed-loop control system for automated solar panel cleaning and monitoring.

IV. METHODOLOGY AND WORKING

A structured design methodology, beginning with a requirements analysis to define core functionalities like cleaning, autonomy, and monitoring. The system architecture was then designed around the Arduino UNO as the central microcontroller, chosen for its simplicity and robust community support. A modular approach was adopted, separating the design into distinct subsystems: the mobility system (comprising DC gear motors and wheels for movement), the cleaning system (involving a mopping motor and a water pump with a tank), the power system (a Li-ion battery paired with a small solar panel and voltage sensor for charging and monitoring), and the sensing/communication system (integrating the DHT11 sensor, PIR sensor, HC-05 Bluetooth module, and buzzer) [20].

Each module was first prototyped and tested individually on a breadboard before being integrated onto a single PCB for reliability. The final robotic chassis was fabricated using lightweight materials like acrylic to ensure traction on panel surfaces. The software was developed in the Arduino IDE, employing a state-machine logic to manage tasks like motor control, sensor data reading, and Bluetooth communication without blocking [21]. A custom Android application was developed using a platform like MIT App Inventor or Android Studio to send commands and receive data, creating a closed-loop user-controlled system [22]. The robot's working is initiated when the user sends a command via the Bluetooth mobile application.

The Arduino, upon receiving the instruction, drives the DC motors to move the robot across the panel [23]. Simultaneously, it activates the mopping motor to scrub the surface and the water pump to spray a controlled amount of water for rinsing. Throughout this operation, the DHT11 sensor continuously measures ambient temperature and humidity, while the voltage sensor monitors the battery level, all this data is packetized and transmitted back to the user's smartphone in real-time [24]. For autonomous recharging, the robot can be positioned such its onboard solar panel is exposed to sunlight, trickle-charging the battery. Furthermore, the user can activate the "Security Mode" from the app, which powers on the PIR sensor [25]. If a bird is detected, the Arduino triggers the buzzer as an immediate deterrent and simultaneously sends an alert notification to the mobile application, informing the user of the potential threat to the solar panel's cleanliness.

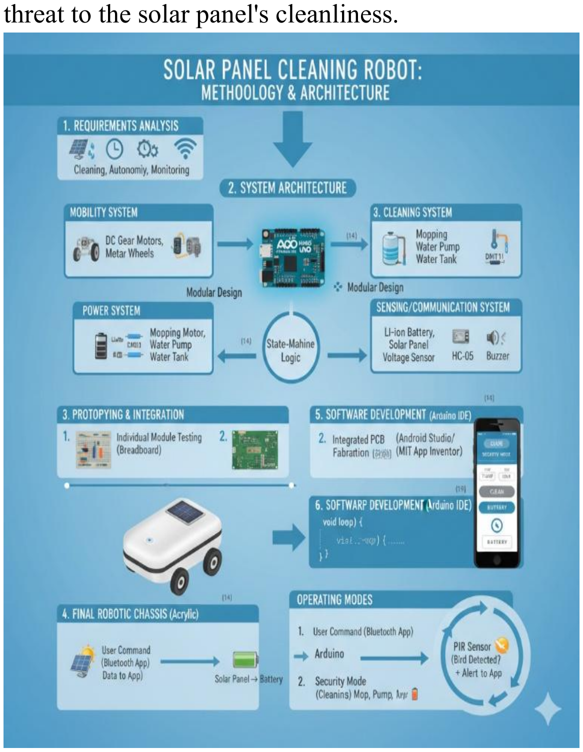

Fig. 3. Block diagram of methodology

V. RESULT

The final results of this research paper gives the details of design, development, and implementation of an IoT-enabled, autonomous robot for optimizing solar photovoltaic (PV) panel performance through automated cleaning and monitoring. The core objective is to mitigate the significant energy loss—which can exceed 15-20%—caused by the accumulation of dust, debris, and bird droppings that typically necessitate costly and hazardous manual cleaning. The proposed system, built around an Arduino UNO microcontroller, offers a comprehensive, remote-operated solution, moving beyond the inefficiencies of traditional methods like manual labour and high-water consumption. The overall architecture ensures a reliable and functional closed-loop control system.

The robot's functionality is achieved through a modular architecture centered on the Arduino UNO. Its primary cleaning mechanism features a mopping motor for scrubbing and a water pump for rinsing the panel surface. For autonomy, the robot incorporates a small onboard solar panel to recharge its Li-ion battery, with a voltage sensor continuously monitoring power levels. The system's intelligence is derived from its bidirectional Bluetooth communication with a custom mobile application, enabling remote control and real-time monitoring. Key environmental parameters, specifically temperature and humidity, are continuously measured by a DHT11 sensor and transmitted back to the user's smartphone. High-power components like the pump and cleaner motor are safely interfaced with the low-power Arduino via Relay Modules.

A defining feature is the integrated security function designed to deter birds, a common cause of panel degradation. This "Security Mode" is activated remotely via the mobile application, powering on the PIR motion sensor. Upon detecting a bird, the Arduino executes a deterrent mechanism: it immediately triggers an onboard Buzzer and simultaneously sends an alert notification to the user's mobile application. The robot's movement and cleaning are initiated by user commands sent via the Bluetooth application, with the Arduino driving the DC motors and activating the cleaning systems. This integrated approach validates the core concept of an efficient, sustainable, and proactive robotic solution for solar panel maintenance, laying a foundation for future enhancements like full autonomy and cloud integration.

VI. CONCLUSION

The prototype is successfully designed, developed, and demonstrated a functional IoT-enabled solar panel cleaning robot. The system effectively addresses the critical issue of solar panel soiling by integrating automated dry and wet cleaning mechanisms, thereby aiming to restore and maintain optimal energy efficiency. The use of an Arduino UNO as the central control unit proved to be a cost-effective and efficient choice for managing the various functionalities, including mobility, cleaning, and sensing. The implementation of Bluetooth communication facilitated the creation of a user-friendly mobile application, allowing for remote operation and real-time monitoring of key parameters such as temperature, humidity, and battery voltage. Furthermore, the innovative addition of an on-demand bird deterrent system using a PIR sensor and buzzer provides a proactive solution to a common cause of panel degradation.

While the prototype validates the core concept, the project also lays a strong foundation for future enhancements, such as full autonomy, cloud integration, and advanced soiling detection. In conclusion presents a comprehensive, scalable, and practical approach to automating solar panel maintenance, contributing to the broader goal of maximizing the output and viability of renewable energy sources.

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