IoT and Computer Vision-based Real-time Solar PV Soiling Monitoring System

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Abstract. To align with decarbonization and energy electrification goals, solar PV systems are expected to gain in popularity in the coming decades. Monitoring PV systems is key to ensuring optimal performance and detecting faults and malfunctions. Faults include partial shading due to physical obstructions, soiling bands, and non-uniform soiling phenomena, which result in localized hotspot heating. The reported work presents an Internet of Things (IoT)- based solar PV monitoring system, which utilizes an ESP32 microcontroller serving as the central processing unit and capable of internet connectivity via WiFi. A range of sensors is used, which serve as an in-built weather station and optical soiling sensor. The collected data is processed and transmitted wirelessly over existing network infrastructure to a cloud-based platform, ThingSpeak, where it is stored, visualized, and analyzed. The combination of electrical and meteorological data provides accurate energy forecasting. Additionally, an independent camera system using a Raspberry Pi as a microprocessor can be used to visually inspect remote modules. This allows for prompt identification of anomalies in power production that may be caused by shading or dirt on panels. Therefore, real-time monitoring can aid in a proactive and dynamic approach to PV system maintenance, optimizing cleaning frequency and energy yield.

1 Introduction

Solar photovoltaic technology is an environmentally friendly way of generating power from solar radiation [1]. It benefits significantly from its modular structure, making it suitable for deployment in small systems to utility-scale power generation installations [2]. The output of solar PV modules is reliant on all ambient conditions they are subjected to, most notably temperature and irradiance [3]. Fluctuations in these conditions are directly related to losses in yield and, therefore, revenue [4]. One such significant cause for energy loss is soiling. Soiling is the deposition and accumulation of any matter on the surface of a PV module, which physically obstructs light [5]. It reduces the optical transmittivity of top surfaces and subsequently the effective amount of solar irradiance absorbed. The loss of power is directly related to the amount or density of soiling material on the PV module [6]. Large utility-scale

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PV plants may experience considerable effects from soiling, especially in arid areas, necessitating system-wide cleaning to alleviate the effects [7]. This results in lower revenues due to higher operating and/or capital expenditures, e.g., for investments in anti-soiling coatings (ASC) or cleaning robots and their maintenance [8]. High solar radiation regions seeing an uptick in PV installations are often dry, desert zones or humid, tropical zones [9]. Dry climates tend to have higher wind speeds, which can result in a higher deposition of soiling particles. These climates also show temperature and humidity cycling, resulting in dew formation on panel surfaces [10]. Moisture on solar panel surfaces increases surface adhesion and makes module surfaces more prone to accumulating dust, even during non-sunlight hours. Therefore, these regions exhibit higher daily soiling rates [11].

Global Solar PV losses due to soiling are owed to an unoptimized cleaning and maintenance schedule, owing to many installations being in remote or inaccessible regions, or poor maintenance practices [12]. Prolonged partial shading conditions are more detrimental to not only to PV output but overall health of PV systems [13]. If shading is for a prolonged period, solar PV cells are put under excess thermal stress due to a localized dissipation of heat. This may lead to hotspot failures and even cracked glass [14]. Furthermore, if dust cementation has taken place, cleaning may involve abrasion or harsh chemicals, which damage panel surfaces and reduce their efficiency and lifetime [15]. Traditional maintenance schedules are not only time-consuming, but also fail to detect hardware malfunction or such harmful soiling on time [16]. Due to the highly sensitive nature of solar PV output to its input parameters, the prompt identification of hardware failures and other anomalies in energy production directly translates into higher energy yield and reduced economic losses due to soiling [17]. Moreover, the damaging cascade of events that takes place due to prolonged unmitigated soiling conditions presents a glaring need for a PV monitoring system that can detect such issues for a dynamic, need-based maintenance approach, rather than the dated, pre-defined frequency-based approach to maximize yield. Several efforts have been made in this direction in order to improve the fault detection due to soiling [18-20]. This work presents a cost-effective, real-time PV monitoring system using IoT to minimize human intervention. It can also be easily extended to other applications in control and PV systems characterization.

2 System Description

2.1 IoT-based PV monitoring system

As the data comprises not only electrical PV output data (DC voltage and current) but also weather data, i.e., ambient temperature, humidity, atmospheric pressure, and irradiance, the analysis of which will provide more accurate energy forecasts and insights. The data processing unit uses the ESP32 microcontroller, which has dual dual-core processors allowing it to simultaneously handle data and compute parameters such as power, while communicating wirelessly to transmit data over a network. Due to the microcontroller module and sensors being low-cost, the overall system remains affordable. It transmits data wirelessly using Wi-Fi to be visualized in a centralized server/ cloud storage platform, ThingSpeak – the data visualization unit of the system.

ThingSpeak is an open-source IoT application by MathWorks that is used to receive and store data from the sensors sent by the ESP32 microcontroller. It uses the HTTP protocol over the Internet via a Local Area Network. The cloud-based server has built-in functions to visualize the data in the channel created by the user. Here, the data is being continuously visualized and stored. The end-user (plant owners, or any stakeholders involved in the decision-making of whether to perform a maintenance task) can access the server from any remote location, view data being published in real time, or retrieve historical data.

In addition to the sensor readings, a Raspberry Pi with a camera module takes images of the PV module at a predefined interval. This provides a more robust monitoring dataset for analysis through machine learning techniques. A block diagram of a PV monitoring system based on the IoT technique is shown in Fig. 1.

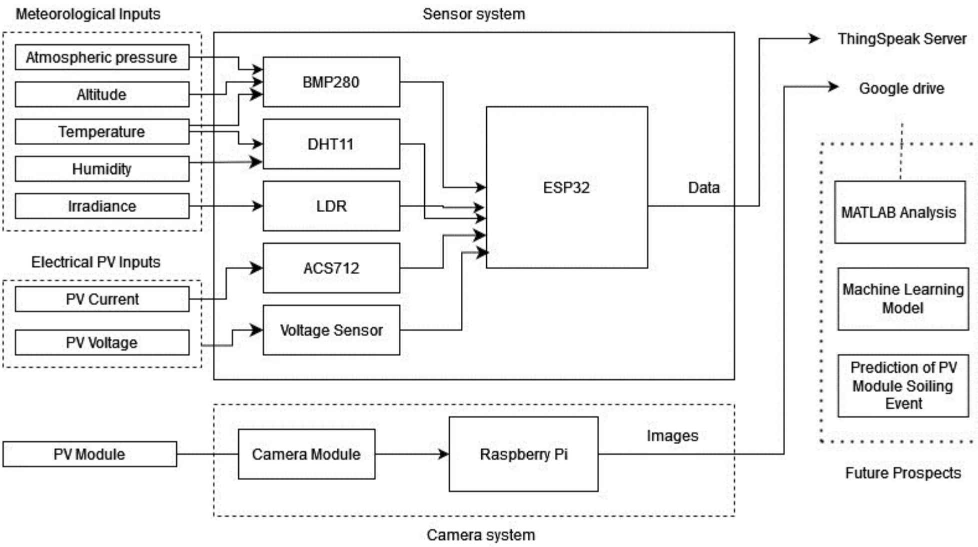

Fig. 1. Block diagram of the overall (sensor + camera) system

This connectivity of objects, i.e., devices with embedded sensors, network connectivity, etc., for data transmission to a cloud-based storage platform over a preexisting network infrastructure, is termed as Internet of Things (IoT). The interconnected IoT devices can communicate autonomously and without external human intervention. Integrating wireless data transfer in PV monitoring systems allows for the remote sensing and control, and automation of data collection. This can greatly enhance performance by improving the accuracy of detecting performance issues and diagnosing faults. Moreover, users may also be alerted when anomalous events take place [10]. Various researchers have implemented solar PV monitoring by coupling various combinations of data processing modules with different data transmission protocols. Fig. 2 depicts CAD visualization of the sensor system mounted on the panel.

Fig. 2. CAD visualization of sensor system mounted on panel

The expression to retrieve PV voltage and current from the analog GPIO of ESP32 is given by equations (1) and (2), respectively, as follows:

$$Voltage, V_{PV} = Analog\ value * \left(\frac{3.3\ V}{4095}\right)\left(\frac{37.5}{7.5}\right)\left(\frac{1.33}{1}\right) \quad (1)$$

$$Current, \mathrm{I} = \frac{(Analog\ pin\ voltage - \ .48)\ V}{0.066\ (V/A)} \quad (2)$$

2.2 Specifications

The PV module specifications and sensor and camera system components is shown in Table 1 and Table 2, respectively.

Table 1. PV Module Data at Standard Test Conditions (STC), 1000 W/m2, AM1.5, and cell temperature 25°C.

PV parameters	Value
Peak Power, W_p (W)	20.0
Power Tolerance Range (%)	+-5
Open Circuit Voltage, V_{oc} (V)	21.8
Max. Power Voltage, V_{mp} (V)	10.0
Short Circuit Current, I_{mp} (A)	1.23
Max. Power Current, I_{mp} (A)	1.11
Maximum System Voltage, V_{DC} (V)	1000
Dimensions (mm)	105x340x25

Table 2. Sensor and Camera System Components.

Parameters	Type
Sensor microcontroller	ESP32
Current sensor	ACS712
Voltage sensor	$V_{cc} < 25V$
Light sensor	LDR
Pressure sensor	BMP280
Atmospheric sensor	DHT11
Camera microcontroller	V3
Camera Module	5MP

Fig. 3 shows the circuit diagram of the designed PV monitoring system based on the IoT technology.

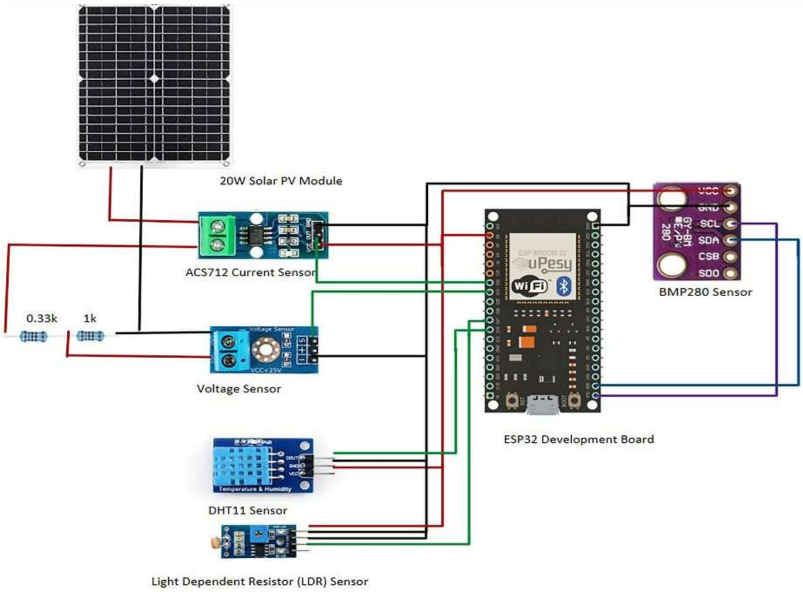

Fig. 3. Sensor system circuit diagram

Various sensors are interfaced with the ESP32 microcontroller using analog-to-digital converters, SPI, and I2C communication protocols. The ESP32 is programmed in the Arduino IDE, in order to send readings to the cloud-based IoT data platform ThingSpeak server. C++ code is linked with C to interact with it. The camera system is programmed to image modules at a predefined frequency and save it locally.

2.3 Hardware Implementation

Fig. 4 depicts the hardware setup for the implementation of the IoT-based PV monitoring system.

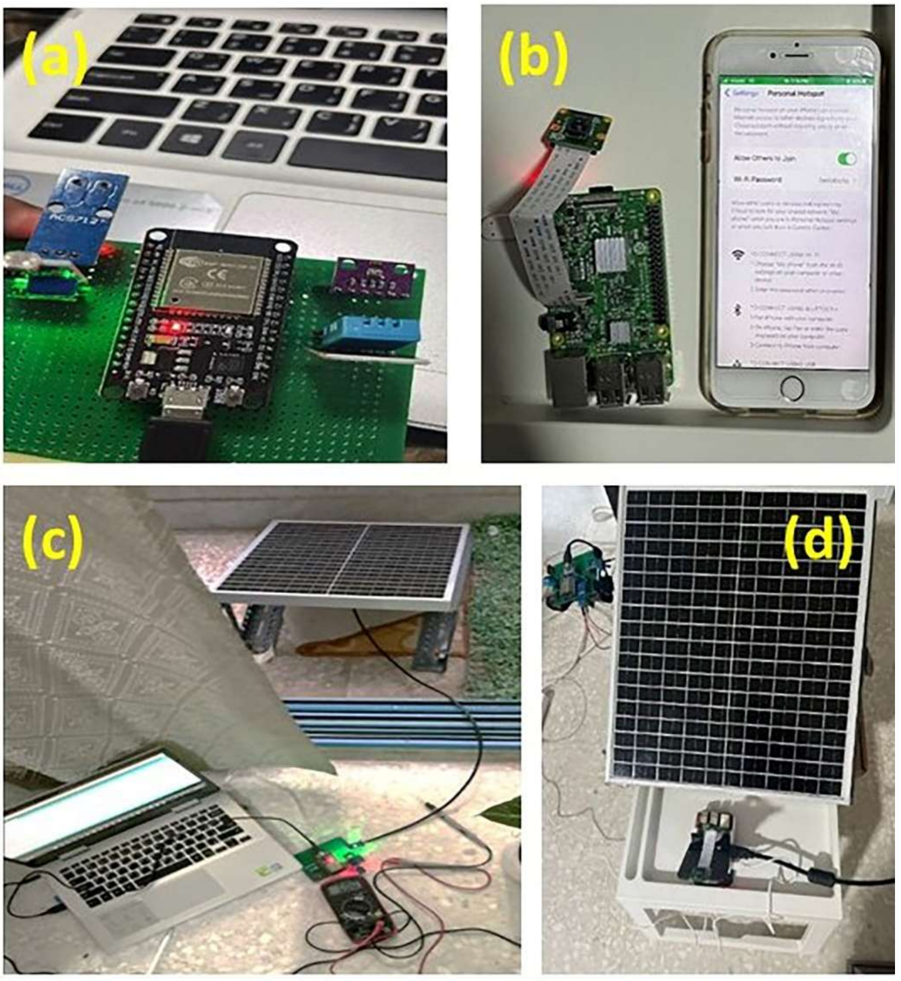

Fig. 4. (a) Sensor system, (b) Camera System (c) Sensor testing setup (d) Imaging setup

2.4 ThingSpeak Data Visualization and Storage

Fig. 5 displays an example of ThingSpeak data visualization measured and collected data such as the PV current, PV voltage, air temperature, and solar irradiance of a PV module for a short period of configuration.

Fig. 5. ThingSpeak Data Visualizations : Collected data of the PV system: Solar irradiance, air temperature, PV voltage and PV current

Images of the solar PV module were taken periodically at a regular interval through the camera imaging system and stored locally on the Raspberry Pi SD card to a file directory without overwriting one another as depicted in Fig. 6.

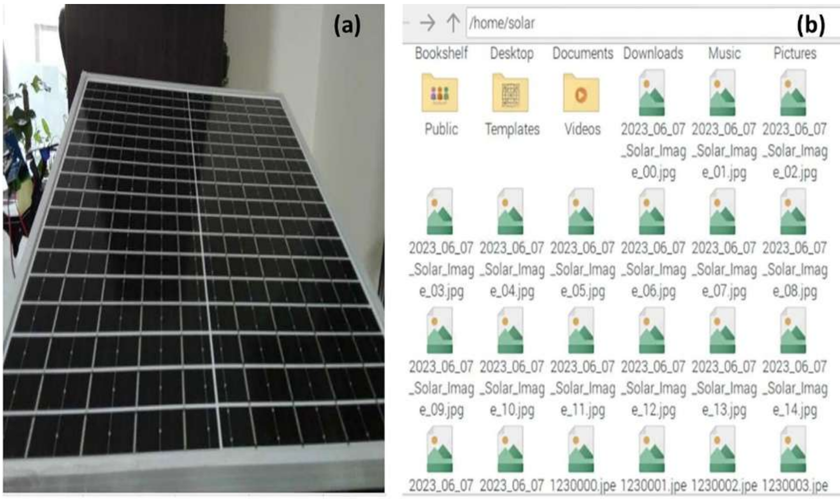

Fig. 6. Camera System PV Module Image (b) Camera System Local Image Storage

By using an ESP32 module as the data processing unit with low-cost peripherals, the system provides the advantage of having benefits of sensor monitoring as well as camera monitoring with a good cost trade-off. The monitoring system records both electrical and weather parameters, constituting a comprehensive dataset. No external I2C, ADC, SPI, or RTC (real-time clock) are required for interfacing with sensors, further driving down cost of the sensor system. The system's in-built ADC s provides a good accuracy of 12 bits, however if required it supports external ADCs for up to 16 bits resolution. The number of modules being imaged is limited by the resolution of the camera. One of drawbacks faced by the IoT systems is the security of applications in its large database. Additionally, existing non smart IoT system will have limitations in their capabilities. The shorter range of Wi-Fi module is another limitation and requires an embedded solution for large scale PV applications. Through further research, the challenges posed by the IoT technology will be overcome and IoT technology will play a critical role in increasing the quality of the monitoring and diagnosis of PV plants. This can benefit the users by enabling them to check their PV systems online, analyze the datasets and predict the evolution of relevant parameters towards fault prediction.

3 Results and Discussion

The 30A ACS712 module required further calibration, typically the offset corresponding to 0A is 0.5*Vcc. The source voltage in the ESP32 is 1.65 V, however this results in a high error in measurement. To identify the actual calibration, actual calibration factor is printing ADC voltage with no current. To account for the noise and subsequent swing in readings, 2000 samples were averaged and before printing to serial monitor, furthermore 100 samples were averaged, providing an ADC voltage of 1.483722 is printed with 6 float decimals. Several scientific figures were selected to be able to read current in the 0.01 A or 100 mA range.

3.1 Accuracy of reading from the Sensor system

Tests were conducted to identify the accuracy in readings by the sensor system in comparison to readings by a digital multimeter. To smooth current values, 250 values were averaged before printing to the serial monitor, following which 40 samples were averaged. An average of 50 voltage samples was used to find the error. Table 3 depicts the current and voltage measurement accuracy.

Table 3. Sensor and Camera System Components.

Parameter	Average system measured values	Digital multimeter measured values	Error %
Current	0.007650278 A	0.0088 A	1.3065025
Voltage	8.52 V	9.907777778 V	7.705535539

4 Conclusion

The primary objective to develop a real-time PV monitoring system has been accomplished, through acknowledging the sub-objectives of measuring PV electrical output and local weather conditions, and transferring this data to the cloud-based platform ThingSpeak, where, in the following is possible: visualization of data, storage of data where the CSV file is appended at the predefined interval. Monitoring is done without human intervention; the data provides plant owners with insights to make better decisions for cleaning tasks, resulting in a dynamic, need-based maintenance schedule. It has been developed for a 20 W system; however, due to the voltage divider setup, this can be scaled up to high-power applications. Ideally, module-level faults can be detected if each module is fitted with a sensor, while also being imaged by a stationary camera module, if costs permit. Otherwise, fitting a string with a single system can provide string-level monitoring.

Although the images provide a robust dataset, ideally, the two systems are linked to complete both monitoring and visual inspection remotely. The system was implemented on a standalone (off-grid) PV system, where it is not subject to any grid fluctuations or rapidly changing environment; therefore, the ESP32s data transmission speed was sufficient for this project. Based on the application, a microcontroller with an appropriate transmission speed and transmission range. Furthermore, data encryption algorithms may improve the security of the network.

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