

Autonomous Photovoltaic Surface Maintenance Using Infrared-Based Dust Detection and Hydro-Mechanical Cleaning Framework for Enhanced Solar Energy Harvesting

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ABSTRACT

The large-scale dust accumulation on solar panels reduces the efficiency of solar panels and increases their maintenance costs. Dust accumulation affects the performance, effectiveness, and energy output of the solar panels. In such a scenario, the optimum gain from the solar panels can be achieved by providing fast and reliable dust cleaning solutions. In the existing literature, researchers have proposed manual or semi-automated solutions that involve monitoring dust levels and adjusting cleaning time. Moreover, the existing solutions lack efficiency and real-time automated dust sensing. In this paper, we will propose an automated solar panel cleaning system by utilizing Arduino Uno, a dust sensor, and a 12V Water pump with an LDR sensor controlled by a 89C51 microcontroller. Our suggested approach provides a smart, real-time dust density detection regardless of the lightning intensity and direction. The proposed system increases solar panel efficiency, extends solar panel life span, reduces maintenance costs, and improves environmental adaptation capabilities. The suggested solution has a deep societal impact by playing a vital role in terms of optimum power utilization by solar panels.

Keywords: Autonomous cleaning systems; Photovoltaic maintenance; Dust detection algorithms; Microcontroller automation; Solar panel efficiency optimization; Optical particle sensing; Hydro-mechanical cleaning.

1. INTRODUCTION

Solar energy represents the electromagnetic radiation emitted by the sun that can be harnessed and converted into usable forms of power [1-3]. It is a renewable form of energy that has been clean and abundantly used for centuries. It has always been the most important and rapidly growing renewable source in the world. It is inexhaustible, but it is also environmentally friendly and offers a long-term solution. The sun is a massive ball of gases, especially helium and hydrogen, because of a nuclear fusion reaction [4] which releases a larger amount of energy in the form of heat and light. A small portion of this energy reaches Earth in the form of solar radiation [5].

Now, one of the devices to store and use Solar energy is a Solar panel, also known as a photovoltaic panel. Their work is to convert solar energy into electrical energy directly. They are made up of interconnected PV cells, usually made up of semiconductor materials, for example, silicon. They absorb sunlight and release electrons, generating a Direct Current (D.C) and can be converted into Alternating Current (A.C.), which can be used to power homes, buildings, power grids, and any other working and

personal place.

The importance of Solar energy has increased due to some environmental effects, such as Fossil fuels, Air pollution, Global warming, greenhouse gas emissions, and more. Many innovations enhance the performance and cost of solar technologies [6]. The solar panel consists of different layers such as Glass Cover, Photovoltaic cells also known as solar cells [7-9], Mono and Poly crystalline silicon, thin film solar cells, back sheet, and frame.

It also has two layers of silicon (N-P type Silicon). N-type has a negative charge, whereas p-type has a positive charge. The electric field between these layers acts as a diode, which will allow current to flow in one direction (From the negative side to the positive side). The electric field at PN type junction [10-11] pushes these electrons to the external circuit, which is generated as a direct current that can later on be converted into alternating current by using an Inverter or can be stored in the battery for use [12-14].

The primary challenge is the reduction in the efficiency and performance of solar panels due to dust accumulation. The Inefficient methods that are used for cleaning the solar panels cause decreased energy and potential damage to panels over time, and in some cases, it is not possible to do the cleaning on a larger scale, for example, solar panel rooftops and solar farms that are eventually not easily accessible. Solar Panel cleaning systems vary, ranging from automatic to manual Solutions [15-16]. It is effective on a small scale, and on a larger scale, it costs more, whereas an automated system offers robotics, water spray, and an air blower to remove the dust accumulated on the solar panel. This system can respond dynamically to environmental conditions. A Comparative analysis reveals that manual cleaning is straightforward and cost-effective, whereas in an automated system, despite its cost in the beginning, it has long-term benefits and high scalability, it also conserves water and reduces the environmental impacts due to dust accumulated on the surface of the solar panel. This project helps to develop an automated solar panel cleaning system, which

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helps us increase the efficiency of solar panels by cleaning the panels and the dust accumulated on them [17-18].

The selected method integrates the water-based solar panel cleaning system controlled by an Arduino Uno microcontroller and dust sensors [19-22]. The system targets the area where the dust is accumulated and then takes action only, when necessary, thus conserving water and optimizing energy [23-25]. In line with recent advancements, related identification and optimization approaches such as fractional input nonlinear output error system modeling [26], auxiliary model-based swarm optimization techniques [27], and novel gazelle-inspired algorithms for nonlinear system identification [28] highlight the growing role of intelligent algorithms in enhancing system efficiency.

The main contributions of the study are:

- Develop a robust automated cleaning system that integrates with the existing solar panel installation
- Incorporate advanced sensors to monitor and detect dust levels on solar panel surfaces accurately
- Utilize a reliable and efficient cleaning method that minimizes water consumption and maximizes cleaning efficiency
- Design a solution that offers cost-effective maintenance and operational benefits compared to traditional cleaning methods
- Ensure the system is adaptable to various environmental conditions and scalable for various panel configurations.

The rest of the study is classified as follows: Section 2 shows the system design, Section 3 shows the software design and implementation of work, Section 4 shows the results and discussion, and Section 5 shows the conclusion and future work.

2. SYSTEM DESIGN

The system is designed to automate the cleaning process for solar panels efficiently. The brain of this system is a microcontroller known as Arduino Uno 3. When the dust sensor detects dust, Arduino processes the data that activates the water pump through the relay module on the predefined threshold.

2.1 Functional requirements

A dust sensor is a sensor used to detect dust particles. These sensors work on an optical or laser-based system to detect the dust particles. When the particles pass through the dust sensor, they scatter light emitted by a laser. The scattered light is detected by a photodetector, which is then converted into electrical signals that help the dust sensor detect the concentration of particles in the air or on the surface of the given object. In this project, when it detects the dust particles, it sends the analog signals to the Arduino.

Arduino is a microcontroller based on the ATmega328P microcontroller. It has 14 digital Input/Output pins, 6 analog input pins, a 16 MHz quartz crystal, a reset button, and a power cable for connecting to a PC or power source. You use Arduino by connecting it to a power source and then putting a code through a program called Arduino IDE and uploading it to the board via USB.

The Relay Module is an electronic device that allows a low-power control system. In simple words, it acts like a switch; it consists of an electromagnet relay, a transistor, and a diode opto-isolator. Input pins include IN, GND, and VCC, whereas output pins include NO, NC, and COM. It also has types of Channels like single channels, 2-channel, 4-channel, 8-channel, depending on the usage and how many devices you want to connect.

The water pump, which is used here, is 12V. The pump is connected to the relay module, which controls its position. It

works based on the commands of Arduino.

2.1.1 Specifications of water pump

- Operating voltage 12V DC
- Flow rate 1.5-2 liters per minute
- Pressure 0.1-0.2 MPa
- Power consumption 15-20 W

Material Corrosion: Corrosion-resistant material usable for outdoor use

The relay module acts as a switch; it helps devices like Arduino to control a large amount of electric current. In this case, it controls devices like a water pump. It controls electrical isolation between the high-power water pump and the low-power Arduino, which ensures the safety of operation in case of emergency.

2.1.2 Specification of relay module

- Operating Voltage 5V DC (Control Operation)
- Switching Voltage Up to 30V DC and 250V AC
- Current Capacity Up to 10V
- Isolation Optical Isolation for Safe Operation

There are also some additional components used as a Resistor, a Capacitor, and a Diode. Explanation of these components is as follows:

- Connection between Arduino and the dust sensor
- Connect VCC to 5V
- Connect GND to GND
- Connect the Output Pin to one of the Input Pins on Arduino
- Connection between the Relay module and the Water Pump
- Connect one terminal of the Water pump to the Common (COM) pin of the relay
- Connect the other to the positive terminal of the 12V Water supply
- The NO terminal of the Relay connects to the Positive terminal of the Power supply
- Connection of the Relay module to Arduino
- Connect VCC to 5V
- Connect GND to GND
- Connect the Control pin (IN) to one of the Digital output pins on the Arduino
- Safety Precautions and Considerations are as follows
- Ensure proper insulation and secure connection to prevent a short circuit
- Use proper and appropriate resistors and capacitors to protect the connection from voltage
- spikes
- Correctly place the diode to protect the server from back EMF, which could damage the
- Arduino and other sensitive components

3. SOFTWARE DESIGN AND IMPLEMENTATION OF WORK

The Arduino IDE (Integrated Development Environment) is used for writing and uploading code to the Arduino Uno. The IDE supports C/C++ programming languages and provides a user-friendly interface for developing, debugging, and deploying code to the microcontroller.

The pseudocode of the software design is as follows:

Set up functions to initialize the Sensor inputs, Relay outputs, and serial communication for debugging.

Continuously read data from the dust sensor and convert it into a usable format.

Compare sensor data against a predefined threshold to decide whether to activate the water pump.

Set the appropriate threshold settings for the sensor according to the environment.

The data is integrated, which helps the system to decide whether it should activate the water pump or not. Explain how the expected dust accumulation rates and the threshold values are determined.

Testing Methodology:

It includes tool setup and procedures for testing purposes. The importance of performing and functional testing to meet its objectives.

- Verify that the subsystem and components operate correctly.
 - Check the Solar panel Cleanliness and efficiency according to the environment.
 - Compare the reading with manual measurements to check the accuracy of the dust sensor
 - Check the system response from sensing to cleaning
- Measure the cleaning process to ensure that it is working properly.
- Observe water usage during cleaning.
 - The calibration process includes adjusting thresholds and initial test results. To improve or modify, make any adjustments to the system
 - Troubleshooting common issues encountered during the provided solutions and testing
 - Environmental factors, sensor placement, and calibration errors lead to sensor inaccuracy
 - Ensure proper wiring, check for faulty components, and verify the control signal from the Arduino, or it can lead to relay malfunction.
 - Evaluate water pressure, Nozzle configuration, and cleaning duration to optimize performance.

4. Results and discussions

Some tests were conducted to evaluate the performance and effectiveness of the Automated Solar Panel Cleaning System, which were concluded on real-world conditions and cases. Data was collected several times as

- Cleaning before and after dust levels
- Water consumption
- Response mechanism and time
- Data has been observed from the dust sensor for the dust accumulated on the solar panel. The average readings of dust level before and after cleaning, Response time, which is between sensing the dust particles and the start of the cleaning process, and water usage in the cleaning process, were recorded as given in Tables 1-3.

Table 1 Dust level before and after cleaning

Test cycle	Dust level before	Dust level after	Reduction
1	360	95	77.7%
2	410	115	74.9%
3	310	82	73.2%
4	340	91	70.4%

Table 2 Response time is between sensing the dust particles to the start of the cleaning process

Test cycle	Detection time	Cleaning starting time	Response time
1	6	9	2
2	9	11	3
3	5	7	2
4	6	9	2

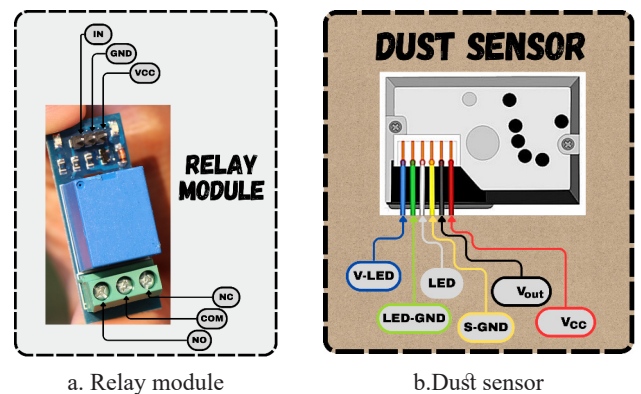
Table 3 Water usage in the cleaning process

Test Cycle	Water Used	Panel Area	Water usage
1	320	1	320
2	310	1	310
3	290	1	290

An average dust reduction of 73% is achieved by the system upon many trials, indicating its efficiency. The sensor provided the correct information across various conditions. Noise reduction and sensor calibration to improve accuracy. The system was strongly stable because no failures were recorded. The Arduino-based system helped us in detecting the threshold’s high reliability and cleaning cycle with minimal delay. The system exceeded or met all the expectations. Some limitations are provided for improvement. It performed well under test conditions.

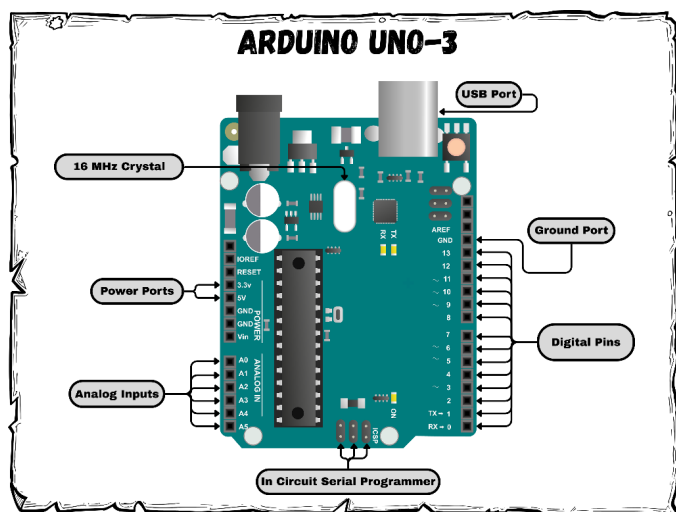
Location, weather, and surrounding activity vary in dust accumulation. Humidity can also affect the sensor readings and their cleaning efficiency. Condensation can also falsely start the cleaning. It is for single-panel setups for larger scale; it will require more power, distributed sensor networks, and a high-water capacity. It gave us good performance in the short term, but for long-term usage and outdoor testing, it remained untested. A weather removal may be necessary, and moisture and radiation, like UV radiation, may result in the reduction of life span. Summarizing the design, Implementation, and testing process, highlight the contributions and the system’s potential to reduce maintenance efforts

The detailed circuit diagram showing the connection between Arduino, Dust sensor, Relay module, and water pump is shown in Figure 1. The real project figure is shown in Figure 2.



a. Relay module

b. Dust sensor



c. Arduino Uno 3

Fig. 1 Detailed circuit diagrams

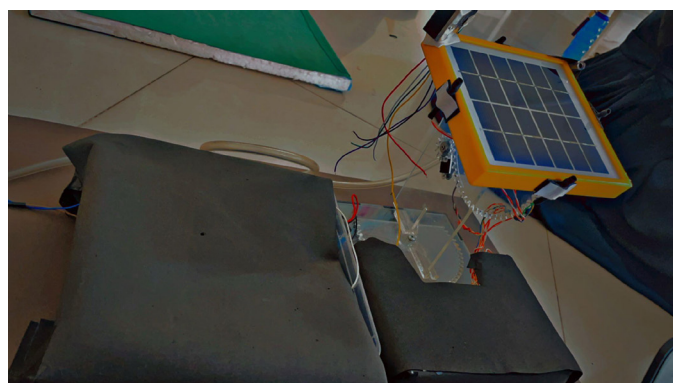


Fig. 2 Real-world picture of the study

5. CONCLUSION

We successfully designed the system for cleaning the solar panels automatically using Arduino Uno and a water pump. The system is designed to maintain the efficiency of removing the dust accumulated on the solar panel. Developed a system that is cheaper and reliable to use, which also minimizes water consumption. In the future, we will use more accurate and advanced sensors for better accuracy. Uses of air blower and rotating brushes, and also optimizes power consumption. We will try to make long-term use of the automated solar panel cleaning system, improving efficiency and maintenance efforts.

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