Smart solar photovoltaic panel cleaning system

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Abstract. With the increasing demand for renewable energy, solar photovoltaic technology is being a topic of concern. However, due to the accumulation of dust and dirt over the panel surface, the performance of the photovoltaic system degrades to a noticeable number. To address this issue: a fully automated, cost worthy and efficient system needs to be invented. This paper presents the design and fabrication process of a prototype able to clean the panel surface. The prototype of this system comprises of a cleaning robot and a cloud interface: the cleaning robot is mobile and able to clean the entire solar array back and forth, with its separately driven cleaning rotatory brush; whereas, the cloud interface is a human-machine interface featuring the distant monitoring and control of the robot. Additionally, to notify the performance of distantly placed solar farm, a sensing unit consisting of sensors was added to this system. Furthermore, to add an automatic cleaning feature, a month-long data of totally clean and dusty panel was processed with regression analysis, and the developed regression model was programmed into the sensing unit. The sensing unit added with the regression model is named as an autonomous unit, as it predicts the suitable time for cleaning action. According to the system evaluation done on a demonstration PV module, it was found that the designed system can clean dry dust accumulated over the panel’s surface. Moreover, by attaching the metal rail tracks on a long solar array, the system seems to be implementable on a large scale solar farm.

Keywords: Solar Photovoltaics, Robot, Distant Monitoring, Regression Model

1. Introduction
Power generation from renewable sources has grown drastically in recent years, due to increasing energy demand as well as the environmental and economic concerns with fossil fuels [1, 2]. Photovoltaic (PV) is one of the renewable energy sources with the greatest future projection as it possesses features such as simple installation, high reliability, low maintenance cost due to the absence of moving parts and zero fuel cost [3]. Solar photovoltaic energy is harnessed from solar radiation; for a monocrystalline solar PV panel under standard test condition, it is seen that only 15-18% of solar radiation is utilized to
produce electricity [4]. Achieving maximum efficiency has been a challenge and this efficiency changes due to several factors like lower irradiance; higher air mass; higher temperature; regardless of this, solar radiation is failed to be harnessed due to accumulation of foreign particles like dust, bird excrement, snow, and many other [4]. Large scale PV systems are immensely affected by dust deposition on solar panels. Conventionally, the panels are cleaned with water and the process is labour-intensive and is proven to be expensive in large scale PV systems [5]. Accumulation of dust particles increases the temperature of the solar panel up to 10% resulting decrease in net output power [6]. It not only increases module temperature but also blocks the solar radiation that can reduce the system efficiency significantly. From an experimental study for two different setups: indoor and outdoor, it is evaluated that the efficiency decreased by around 30-40%, and in particular, moss deposition could reduce the output power by up to 86% [7]. An average of 1% with a peak of 4.7% in two month observation period was observed in the United States, 40% degradation in 6 month period in Saudi Arabia, 11% decrease in efficiency in the tropical climate of Thailand and from 33.5-65.8% reduction in efficiency from a study conducted in Egypt [8]. Making consideration to reviewed facts and figures interlinked with efficiency reduction, significant improvement in the output of the solar panels can be achieved by an effective method of cleaning. There have been numbers of solar panel cleaning technologies [4], although very few or none of them include condition-based solar panel cleaning. Dust covered solar photovoltaic panels might not need cleaning, or maybe cleaning action performed just due to visual inspection might not be effective in terms of economics. In fact, it is necessary to analyse that, whether the investment used to perform cleaning action covers the investment itself and regains the performance which was degraded due to dust deposition. Upon looking at the necessity of effective solar panel cleaning system, the prime objective of this study is to prototype a smart system able to monitor the condition of a solar power plant and decide the right time to perform cleaning action.

In this paper, a solar panel cleaning system is presented with an isometric 3D sketch for its implementation on large scale solar farms. The developed prototype consists of three major units: Robotic, Autonomous and cloud. The robot was designed using a free body diagram thereby addressing the dynamics whereas, the autonomous unit was equipped with few sensors to update the condition of the solar panel. To achieve an automatic cleaning feature, a regression model was programmed in the processor of the autonomous unit. Human-Machine, as well as Machine-Machine interfacing, was achieved using third party cloud-based interface named UBIDOTS. With complete prototyping, a 3D sketch was done to represent the practicality of the Smart Solar Photovoltaic Cleaning System in solar farms. The novelty of this study lies within the implementation of the Internet of Things and the autonomous cleaning feature. However, some techno-economic analysis is required before implementing the proposed cleaning system as depicted by the aforementioned sketch.

2. Model Development
The developed model consists of two different units: Robotic Unit and Autonomous Unit. The two units communicate through an internet cloud-based platform known as UBIDOTS. Robotic Unit acts as a slave unit, as it follows command either from the autonomous unit or from the UBIDOTS interface directly on the operator’s demand. The motors move the robotic unit back and forth through the rails over the panel. Two limit switches are placed at the right and left end to sense the end of the panel array. Also, the robotic unit consists of a rotational brush that cleans the panel as the unit moves.

The autonomous Unit, known as the master unit, sends the command to the robotic unit to perform cleaning action. This unit comprises sensors to sense light intensity, dust density, temperature/humidity, and output power in order to generate automatic cleaning signal and display the condition of solar panels/farm. The important three variables: illuminance, current, and voltage (output power) are taken as the input parameter and real-time slope is calculated. This real-time slope is compared with the slope of the reference line. If the real-time slope is less than the reference slope, the master unit sends a cleaning command to the slave unit. The autonomous unit keeps on sending commands unless the performance of PV is recovered. Figure 1 represents the flow of automatic cleaning and gives a thorough review of the working of the robotic and the autonomous unit.
A cloud-based interface is used for human-machine as well as machine-machine interfacing; for the prototyping, third party web-based platform named UBIDOTS is used.

![Flowchart of the Proposed Model](image)

**Figure 1.** Flowchart of the Proposed Model

3. Prototyping the Robotic Unit
In the following subsections, prototyping of the robotic unit is explained.

3.1. Idea Generation
The question regarding the cleaning method used by the robot, its movement across the panel as well as adjacent panel is addressed by selecting the best choices among the listed ones in Table 1.

To achieve effective cleaning, the roller was selected as the best cleaning method among all other methods. To avoid the stress of cleaner weight and to achieve better mobility, movement across the panel and adjacent panel was expected to be achieved by attaching a separate rail at top and bottom ends.

| Cleaning Method          | Movement Across Panel | Movement between adjacent panel |
|-------------------------|-----------------------|---------------------------------|
| Air/Water Jet           | Wheels                | Three bar mechanism             |
| Mop                     | Suckers               | Make a bridge                   |
| Scrubbing               | Rails                 | Spring System                   |
| **Rollers/Rotational**  | Caterpillar Tracks    | **Attachment rails**            |
| Vacuum                  | Detachable Pulleys    | Flying                          |
| Wiping                  | Hover/flying          | Big wheels                      |
3.2. Design Evaluation and Selection
Several designs were sketched and among them the best design: the robotic design was proposed and proceeded towards the fabrication process. Different designs along with their defects are shown in Table 2.

| Design                      | Defects                        |
|-----------------------------|--------------------------------|
| Chain Sprocket Design       | Impracticable for Large array  |
|                             | Sagging of chain               |
| Threaded Bar/Nut Design     | Fixed System                   |
|                             | Slower                         |
| **Robotic Design**          | **Separate Power Supply Required** |

The reason for selecting a robotic design is primarily associated with its large-scale application and portability. The requirement of a separate power supply for robotic design can easily be addressed by the use of either a lightweight battery or a separate solar module or both, over the top of it, which can supply the required power.

3.3. Torque Requirement of the selected design
The torque requirement of the motors used to drive the robot is evaluated using a free body diagram as shown in Figure 2. It is to be noticed that the weight of the robot is approximated by adding the weight of individual components to be fabricated. To calculate the torque required, it is assumed that the sine component of the total weight of the robot is exerted at the upper end of rails, whereas the cosine component exerted at the lower end: under equilibrium condition.

The force required on the lower part of the robotic unit is given by Equation 1 and 2:

\[ F_d = \mu N_1 \] (1)

\[ F_d = \mu mg \cos \theta = 0.2 \times 5.37 \times 9.8 \times \cos 30^\circ = 9.11N \] (2)

The torque required on the lower part of the robotic unit is given by Equation 3:

\[ \tau_d = F_d \times \text{radius of wheel} = 9.11 \times 3.5 \times 10^{-2} = 0.3189Nm \] (3)

Thus, the force and torque required on the lower part of the robotic arm are 9.11N and 0.3189Nm respectively.

Similarly, for the upper part of the robotic arm we calculate force and torque using Equation 4, 5 and 6:

\[ F_u = \mu N_2 \] (4)

\[ F_u = \mu mg \sin \theta = 0.2 \times 5.37 \times 9.8 \times \sin 30^\circ = 5.2626N \] (5)

\[ \tau_u = F_u \times \text{radius of wheel} = F_u \times 3.5 \times 10^{-2} = 0.1482Nm \] (6)

Where,
- \( \mu = 0.2 \) (the coefficient of friction between mild steel and plastic tyre) [11]
- \( m = 5.37 \) kg (mass of robot)
- \( N = \) Normal Reaction force
- \( g = 9.8 \) m/s\(^2\) (acceleration due to gravity)
- \( \theta = \) Tilt angle
- \( \tau = \) Required Torque

![Figure 2. Free body diagram of the robotic unit](image)
surface whereas, at the lower end, it is parallel. Hence, to match with the above torque requirement, the appropriate motor with motor torque greater than 0.3189 Nm and 0.1482Nm is to be selected

### 3.4. 3D Design and Fabrication of the robotic unit

The 3D design of the robotic unit is shown in Figure 3, which majorly consists of stepper motor for translational motion, PMDC (Permanent Magnet Direct Current) motor for the rotatory motion of cleaning brush, control circuitry box, power supply solar module. The fabricated prototype is shown in Figure 4 mounted on a demonstration solar module of 50 Wp.

![Figure 3: Robotic Unit: 3D Model](image)

![Figure 4: Robotic Unit: Fabricated Prototype](image)

### 3.5. Control Circuitry

The prototype of the robotic unit is operated by a microprocessor named particle photon; and has motor drivers for each motor controlled by the digital pin of the microprocessor. Particle photon is capable of communicating solely with the cloud through an inbuilt wi-fi antenna connected to a wireless network connection.

### 4. Prototyping the Autonomous Unit

The autonomous unit consists of sensors and a microprocessor: Particle Photon. Data from sensors are taken by the I/O pins of the microprocessors. Particle photon communicates with the cloud in the same manner as in the robotic unit. The autonomous unit mainly features real-time updates of the solar farm and automatic cleaning, when performance degrades below a specified limit, using a pre-programmed regression model.

#### 4.1. Parameters and associated sensors

The autonomous unit prototype monitors input, output and influencing parameters which are directly or indirectly associated with the output power of the solar farm. In the prototype, the light intensity is measured using an illuminance sensor (TSL 2561), the output power is measured using voltage and current sensor; additionally, influencing parameters like temperature and humidity are measured by DHT11 temperature and humidity sensor whereas, dust density is measured by a GP2Y1014AU0F dust sensor.

#### 4.2. Automatic Cleaning

The prototype of an autonomous unit is intended to generate a “time to clean” signal when the performance of the solar farm degrades below the specified limit. An experimental set up is done to develop a regression model by collecting data from two different scenarios: a totally clean and completely covered dusty panel. The developed regression model is programmed in the microprocessor such that it detects the worst condition when the panel needs cleaning action.
4.3. Experimental Set-Up and Regression Model
An outdoor experimental set up was done at Suryabinayak-09, Bhaktapur, Nepal (27°39'10.3"N, 5°27'37.2"E) using demonstration module (50 Wp) inclined at 30° facing south. The experimental setup was left under natural sunlight condition for both with and without dust scenarios covering most of the illuminance’s values from, cloudy to clear and day to night. The value of illuminance and output power is taken and saved at the cloud interface. It is to be noted that the sensor used to measure input sunlight has limitation up to 40,000 lux [12], whereas at clear sky condition it is found to be 107527 lux [13]; so, the output power beyond 40,000 lux is also considered with its approximated illuminance value.

The raw data collected from the experimental set up was retrieved from the cloud interface and processed through data pre-processing techniques: transformation to reduce noise and variability, feature selection to remove redundant and irrelevant data. Afterward, regression analysis of the processed data is done to find the relationship between the input variable: illuminance and output variable power. On finding the linear relation between input light and output power, lines of best fit using the least square method are plotted from the regression analysis so done as shown in Figure 5(a & b). The equations of the line of best fit were $y = -1.58 + 0.67x$ for a clean panel; and $y = -0.02 + 0.33x$ for a panel with dust.

![Figure 5. Output Characteristics of a) Dusty Panel b) Clean Panel](image)

Figure 5: Output Characteristics of a) Dusty Panel b) Clean Panel

![Figure 6: Zone of Operation for Automatic Cleaning](image)

Figure 6: Zone of Operation for Automatic Cleaning
A regression model is developed by combining both linear regressions in a single plot. Slope of two lines of best fit were averaged as in Equation 7, which defines the zone of operation as shown in Figure 6 by shaded portion under the green line. This zone of operation defines the condition, whether the solar plant requires cleaning action or not. If the coordinate defined by solar input and output power at any instant of power generation falls inside the zone of operation, the autonomous unit either notifies the operator or commands the robotic unit that cleaning action is required. The coordinate at particular instant along with the origin is joined to represent a line, whose slope termed as real-time slope as shown in Equation 8 is compared with the reference line assuring that the coordinate falls under the zone of operation.

\[
\text{Slope of Reference Line (mr) = Slope without dust (mc) + Slope with dust (md)}
\]

\[
\text{Real – Time Slope (mt) = \frac{\text{Real – Time Power (P(t))}}{\text{Real – Time Illuminance (I(t))}}}
\]

5. Discussions and Findings

The accumulation of dust might not affect significantly in case of small-scale production, however, if the production is in the range of megawatts, even a 1% reduction in efficiency might significantly affect the IRR (Internal Rate of Return) of the project. Smart Solar Photovoltaic Panel Cleaning System is mainly focused on its application in large scale solar farms having uniform solar arrays throughout the plant.

5.1. On Making Site Visits

Smart Solar Photovoltaic Panel Cleaning System can be used in two different ways depending upon the site location. If the site is near, it is suggested to implant a single autonomous unit at the site which monitors the condition of the plant: output power, input light energy, temperature, humidity, dust density. Whenever the autonomous unit detects the performance of the plant inside the zone of operation, it alerts the operator and suggests to perform cleaning action using a single robotic unit. The same robot is detached from the array and transferred to the next array using human labour, after cleaning the complete array back and forth; this process is continued until the whole solar farm is cleaned. The advantage of this type of cleaning procedure is that it requires a single robot, meaning lesser investment in robotic unit.

5.2. Without site visit

If the site is very far to reach involving high transportation costs, or if the site is subjected to the frequent sand storm, it is suggested to implement a different model. Solar panel cleaning in the aforementioned site can be cleaned without making a site visit, and to do so: multiple numbers of the robotic unit need to be placed on each of the arrays. An autonomous unit is placed to sense the real-time condition of the

![Figure 7. 3D modelling of the cleaning system with robots at each of the arrays](image-url)
site as mentioned earlier before. The autonomous unit is considered as the master unit and commands robotic units to clean their respective array; else looking upon the condition of the plant, operators themselves can command robotic units remotely. If transportation to the site becomes expensive in comparison to multiple robotic unit installations, the site can be modelled as shown in Figure 7. Pyranometer is seen instead of a luminosity sensor used in the prototype, which entails accuracy in regression model and ensures better performance of the autonomous unit.

6. Conclusion
In this paper, an Internet of Things based model naming Smart Solar Photovoltaic Cleaning System is presented, mainly focusing its implementation on a large-scale solar plant with standard panel configuration. It is to be noted that the automatic cleaning is proven to be most effective for a large solar farm located in semi-arid areas, where frequent cleaning is required due to sand deposition. Additionally, before implementing the proposed model of Smart Solar Photovoltaic Panel Cleaning System, a cost worth based economic analysis must be done to make sure that the investment a plant owner willing to make on cleaning system will generate revenue in accordance to plant size, location: majorly the environmental conditions that the plant is subjected to.

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