

## Autonomous Circular Robot for Solar PV Panel Dust Cleaning Based on an Arduino Kit

Sanabel Muhson Alhaj Zber<sup>id</sup>, Ali N. Hamoodi<sup>\*id</sup>, Hiba-Allah T. Abdullah<sup>id</sup>, Farah Isam Hameed<sup>id</sup>

Technical Engineering College, University of Mosul, Mosul 41001, Iraq

Corresponding Author Email: [ali\\_n\\_hamoodi74@ntu.edu.iq](mailto:ali_n_hamoodi74@ntu.edu.iq)



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### ABSTRACT

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*solar system, dust, soiling, cleaning robot, Arduino*

One of the primary environmental issues that reduces the electrical output of photovoltaic (PV) panels is the dust that accumulates on them. This research focuses on cleaning a single solar PV panel with an Arduino-based circular cleaning robot designed to remove dust accumulated on its surface. Evaluating the panel at various time intervals and dust accumulation levels reflected on the panel's electrical performance using the methodology documented in the literature on soiling and power loss. Cleaning dust off solar panels reduces dust accumulation and restores performance to a 95–98% power range, up from an extreme low of 65–75% efficiency. The difference in the solar panels' performance due to neglected dust cleaning is a 20–30 percentage-point increase in efficiency. This research study confirms that a low-cost circular cleaning robot, which operates without the need for water, provides solutions to the economic problems of PV performance maintenance in areas where PV panels are manually cleaned, an intensive process that stresses water scarcity. This work confirms that the area of maintaining neglected PV systems, particularly in terms of performing dust cleaning at economic costs due to labor intensity and water scarcity, is an area for investment. Therefore, the research study confirms that operational sustainable PV systems with flat dust-accumulating surfaces robotic technology have a place to mitigate the increase of PV systems maintenance costs in the future.

## 1. INTRODUCTION

Cost-effective and adaptable to different scales, solar photovoltaics (PV) technology is one of the leading, most quickly evolving, and most flexible renewable technology alternatives in the world today. Performance optimization of PV systems, however, is dependent on the mitigation of several environmental factors. One of the most significant threats to energy generation in the inter-tropical, arid, and semi-arid climate regions of the world is the accumulation and the less the rainfall, the worse the blockage. Dust on the surface of PV modules decreases the short circuit current and maximum power output of the module by obstructing sunlight and other protective glass layer transmissions. Many performance analyses of the dust accumulation phenomenon have been documented. Dust accumulation has an exponential effect on efficiency loss of PV modules, as studies have shown that even a thin layer of dust can cause a reduction of 10–20% in the power output within the module. Additionally, more extensive dust accumulation can cause a 30–50% reduction in output efficiency, depending on the climate conditions and the specific dust characteristics [1, 2]. Further studies in desert conditions have shown that daily dust, accumulation on PV panels can cause a 0.2%–0.5% loss in power output [3, 4]. In the Middle East and North Africa, damage caused by dust storms and a high concentration of particulates and aerosols in the atmosphere makes the PV dust accumulation issues even more challenging. In the study of Iraq, PV modules that were

left uncleaned for three months and used for street lighting applications suffered a reduction of up to 59% in their power output, highlighting the need of maintaining the energy production through periodical cleaning [5, 6]. All this evidence shows that environmental dust accumulation is not merely an irritant, but a significant operational and economic concern for the PV systems. In large PV installations or in areas of low water availability, reliance on traditional cleaning method, which use manual labor and large amounts of water, becomes unpopular. This has led to the development of robotic systems for PV cleaning, which have proved to be very promising. Commercial systems, autonomous dry-cleaning robots, show significant recoveries in PV performance without the need for water [7]. However, many of these systems are expensive and technologically complex, preventing widespread use in developing areas or for small, low-technology installations. To solve these problems, researchers have studied low-cost, microcontroller-based cleaning robots, particularly Arduino. It is a flexible and affordable microcontroller that allows for motor control, navigation, and the use of basic sensors. Several engineering projects have shown Arduino-based linear or mobile cleaning systems, uses dry brushes, wipers, or rolling cleaning chassis [8, 9]. Interest is growing, yet the academic literature is lacking in actual performance assessments of such robots in actual field conditions and natural dust build-up over time. This study examines the dust cleaning and performance recovery through the use of an Arduino-based circular cleaning robot. It was

investigated over a single PV module was subjected to natural environmental soiling at various time intervals. As the module's operational state was monitored at different dust accumulation levels, the correlations between soiling and power loss were drawn from the literature. This establishes a scientific foundation for robots effectiveness. The results help close a vital gap in the research. Demonstrating how inexpensive, waterless robotic cleaning can reduce the performance losses experienced in dusty regions and improve PV installations' sustainability, a comparison between circular robot and traditional methods for solar PV cleaning is:

Circular robot solar PV cleaning offers enhanced safety, water conservation for large-scale farms and efficiency, while in contrast traditional manual cleaning is setups but risky and labor intersave. it is more consistent, improving energy yield and covering more area, in addition to water saving for arid areas because considers waterless or needs minimal water also reduces human risk and labor of accidents or damage. These systems operate autonomously and are suitable for large, remote area microfiber cloths and airflow technology are used to remove dust effectively.

## 2. LITERATURE REVIEW

The literature survey illustrated by these three studies:

### 2.1 Impact of dust accumulation on photovoltaic performance

Reduction of solar irradiance due to dust deposition has been well documented across different climates. Dust may impede the transmittance of the glass cover, directly lowering the short circuit current ISC and power at the maximum point Pmax. It was shown that moderate dust accumulation could decrease power output by 15% - 30% [1] while performance degradation was found to vary significantly with dust type, size distribution, and relative humidity [2]. In desert climates, non-cleaned solar panels for an extended period of time may suffer power loss over 40%, which is a common and extreme case documented for a series of long-term measurements [3].

### 2.2 Cleaning methods and robotic systems

Soiling losses have resulted in a wide range of cleaning technologies being proposed. Manual cleaning, while effective, is labor-intensive, dangerous, and requires a lot of water. In the case of automation, water-spraying systems, wipers, electrostatic dust repulsion, and robotic brushes have been introduced. In large commercial solar farms, dry cleaning robots on rails have been shown to recover power yield significantly and are therefore common in practice. More recent studies have highlighted the importance of cost-efficient dry-cleaning methods because of water scarcity and maintenance cost reduction needs [10].

### 2.3 Arduino features and applications: Cleaning robots

Considering the need for flexibility and affordability in robotic controllers, Arduino microcontrollers, including the Arduino ecosystem, provide opportunities in sensor and motor outfitting for simple programming and open-source hardware. Engineering research showcases the Arduino innovations, cleaning robots for primary and small PV arrays. DC motors, limit switches, dry brushes, and actuators have engineered

with low-weight and low-cost options for cleaning. Engineering design has led the studies with little focus on performance metrics for Arduino automated robotic cleaning systems. Published research demonstrating the effectiveness of automated cleaning robotics engineered with Arduino in improving performance metrics is lacking. The automatic cleaning of solar PV panels focuses on the accumulation of dust on the panels, particularly in dusty environments such as tropical countries like Iraq. To ensure optimal generation, it is necessary to keep PV panels clean and free from dust. This system incorporates sensors to detect dust on the panel surface, using an Arduino controller with sensors to address the issue of dust accumulation on the PV panel and aims to achieve optimal production [11].

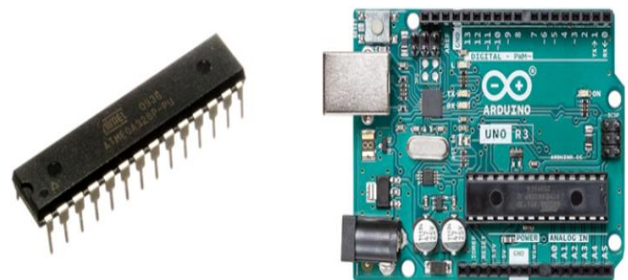
## 3. SYSTEM DESCRIPTION

### 3.1 Overview of the cleaning robot architecture

This particular model of a cleaning device is constructed around a mobile robot with a circular base and a rotary dry scrubber designed for the removable cleaning of dust particles from the PV panel surface. The robot is designed to work directly on the module surface and is capable of traversing the length of the module under the command of an Arduino microcontroller. The system is designed to offer an economical, autonomous, manual-free, and waterless cleaning method that can be used to restore PV outputs, thus making it ideal for water-scarce, desert-like areas. The circular chassis houses the robot and all of its components, including the motors, battery pack, Arduino, and the structure that mechanically supports the brush. The robot performs a number of passes over the surface of the PN module, and during each of these, the rotating brush releases accumulated dust, which is subsequently removed during a sweeping action.

### 3.2 Arduino microcontroller unit

The control system is based on the ATmega328P microcontroller on the Arduino Uno board as shown in Figure 1. This Arduino board was selected because:



**Figure 1.** The ATmega328P microcontroller is included in the Arduino Uno board

- Cost and availability: The Arduino boards are easily available and inexpensive, which makes them suitable for designing and implementing scalable educational projects.
- Ease of programming: The Arduino environment allows for the use of simple C and C++ programming languages, which facilitates the rapid refining of the movement optimization.
- Flexible I/O capabilities: The Arduino Uno board includes

eight I/O digital I/O pins, which allow for the control of the motors and limit switches. There are also 6 PWM channels, which allow for the control of speeds to ensure control is precise. Also, there is an onboard ADC, which may come in handy to add more sensors.

•Community and document support: The platform is an established means that offers support to users and communities, therefore diminishing the efforts of design and troubleshooting. For this robot, the Arduino is the primary controller, which:

- Drives the propulsion motors using an H-bridge motor driver.
- Controls the motor that rotates the brush used for cleaning.
- Used to monitor the limit switches that are located at the two extreme ends of the panel.
- Executes a predetermined cleaning routine that is a sequence of moving in the forward and reverse directions.

### 3.3 Mobility and mechanical design

The motion components of the robot consist of 2 DC motors installed at the opposite ends that provide a differential drive so that the robot can:

- Travel along the PV panel
- Keep balance during the rotation of the brush
- Reverse the motion

The circular design of the robot chassis reduces the potential spots for friction to occur and evenly distributes the weight throughout the chassis. This design also optimizes the brush to cover a greater surface during each cleaning run, making the robot more efficient at cleaning than linear cleaning mechanisms.

### 3.4 Cleaning mechanism of the dry brush

A cylinder or circular brush spins at an exact angular speed that is adequate to impart enough mechanical action to eliminate fine dust resting on the surface of the panel. This dry brush works best for:

- Areas lacking water
- Areas with high dust accumulation
- Low to moderate soil conditions

Research studies indicate that dry brush cleaning can achieve up to 80-95% of the solar panel's functionality at no moisture expense, hence best suited for sustainable cleaning, in order to maintain the robot stability on a slope (tilt angle), manage interaction between friction and gravity has been adopted in the design circular cleaning robot is designed with low center of mass and its vertical projection must stay within the boundary of robot wheel base in addition to the materials which used in the wheels also, the adaptability to non-ideal weather like high winds and rain the aerodynamic (circular shape) unlike boxy design where the wind flows around the cylinder with less drag which in turn will reduce the risks. The robot is being pushed off or flipped. Ingress (IP ratings) production enables the robot to face the rain.

### 3.5 Power source

A robot uses a compact lithium rechargeable battery of 7.4 V and 12 V. The power system provides: Present ability to sustain the demands of drive motors steady voltage to support the Arduino board. Continuous cleaning operation without external or manual connections. In future models, we

anticipate solar-powered battery recharging.

### 3.6 Flow of operation

One side of the PV panel has the robot. The Arduino system starts the brush movement as well as going forward. There is a limit switch at the other end that triggers to reverse the motion direction. After the robot makes a set number of passes over the panel, it will stop when the panel is clean enough. According to the logic set, the robot has the option to stop on its own or be stopped by a user.

## 4. METHODOLOGY

The methodology of developing a solar PV panel using circular robot included a systematic approach to design effective cleaning, a develop and environmental conditions. The Circular robot mechanism, electrical and software components have been designed and developed to meet these requirements [12, 13]. The design of a circular cleaning robot is similar to a Vacuum bot, with easy maneuverability around the solar panel corners [14, 15].

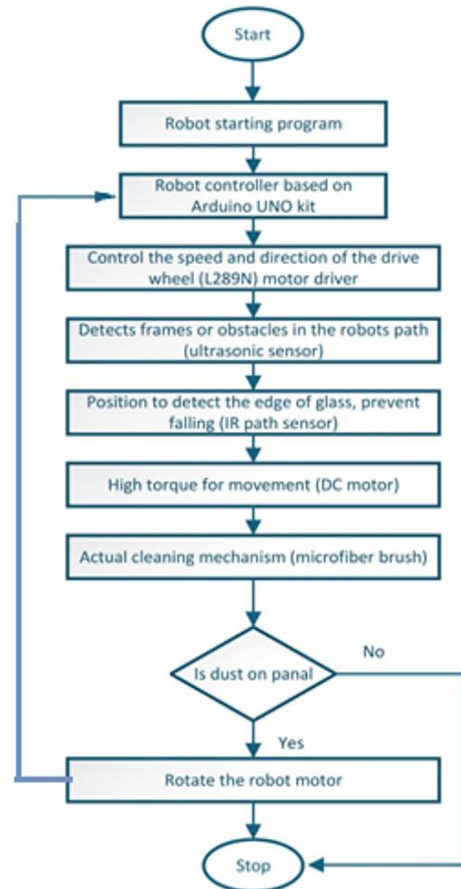


Figure 2. Flowchart circular dust cleaning of solar photovoltaics (PV) panel

- Locomotion: Two geared DC motors. at the robot center and two caster wheels in front and back for providing Stability.
- Adhesion mechanism: High vacuum suction high friction silicone wheels motor or used to prevent the robot from sliding down the glass when the PV Panel is felted in 10°-30°.
- Cleaning module: Dual circular brushes made of soft microfiber to remove dust without scratching the glass.

Figure 2 represents the flowchart of circular robot that used for solar PV dust cleaning and the mechanism of movement, visual area inspection method was used to determine the cleaning ratio to give a good decision for one panel but not proffered to use this method for many panels or array light transmittance was evaluated from the optical quality of the PV cover glass and encapsulate over time factors such as, yellowing of the polymer can reduce the photons number from reaching the silicon cells and image analysis gives a distinct benefit over single point sensor due to it is ability to make a map the spatial distribution of light loss across the entire panel.

#### 4.1 Experimental setup

Only one solar panel was used in the assessment, as shown in Figure 3. The solar panel was deliberately exposed to dust, staying in the outdoors for varying amounts of time. At every time interval, the dust covering the panel was evaluated, and so was the performance level of the panel, in estimation, to determine the effectiveness of its functioning.

The panel was colonized by a small, autonomous dust-removing robot, such that the panel could enable real-time dust mitigation in the field. Each of the panel-cleaning missions occurred under real dust, outdoor, and wind conditions, instead of a controlled lab. The results can, therefore, be used in real-life applications and avoid the limitations that laboratory data may introduce.



Figure 3. Solar panel with cleaning brush

#### 4.2 Soiling-efficiency estimation model

This study does not measure the electrical power output from the solar PV systems. Instead, it relies on documented empirical dust changes and professional solar PV performance loss relationships from published literature, such as Benyadry et al. [2], Shahzad et al. [8], which have shown the following percentage losses from dust cover.

- Light soiling → 5–15% reduction
  - Moderate soiling → 15–30% reduction
  - Heavy soiling → 30–50% or more
- Using the above, each planned dust condition was assigned:
- A specified percent cleanliness (0–100%)
  - A computed percent PV efficiency.

For instance, a heavily soiled panel with an estimated 60–70% cleanliness level is expected to have an efficiency rating of 65–75% and a clean panel with a cleanliness level of 92–97% is expected to have an efficiency rating of 95–98%. Such mapping is common practice in soil studies in which the power output is not feasible to measure.

#### 4.3 Evaluation procedure

As time passed, the dust built up on the PV panel over time passed, the dust built up on the PV panel over time.

Before the panel was cleaned, the stages of dust buildup on the panel surface were rated. The robot was activated to make several passes for the cleaning of the solar panel. Once the dusting was completed, the panel was evaluated to find out the following [16-20]:

- Cleanliness improvement
- Estimated improvement in efficiency

The results showed the difference between the dirtiest and the cleanest solar panels after dust removal, and an improvement in efficiency was calculated.

#### 4.4 Performance metrics

There were two main KPI's.

##### 1. Surface Cleanliness (%)

How clean the PV surface is when compared to the hypothetical situation of being clean.

##### 2. Relative Electrical Efficiency (%)

Calculated based on the soiling-loss relationship from the research articles.

The improvement from cleaning is calculated as:

$$\Delta\eta = \text{Before Cleaning } \eta - \text{After Cleaning } \eta \quad (1)$$

This metric indicates the actual gain from implementing the cleaning robot.

### 5. RESULTS

The six evaluated conditions were summarized in Table 1 along with their respective cleanliness percentages and estimated relative power efficiencies. These conditions were sorted from dirtiest to cleanest, with the dirtiest being Rank 1 and the cleanest being Rank 6.

#### 5.1 Brush cleaning cases

Robotic brush system for cleaning solar PV panel is designed in various configurations to handle specific environmental conditions such as desert dust. These brushes automated vehicle that traverses the PV panel from Figure 4 to Figure 9, representing the cleaning stages. Numbering: Make sure that the placement and numbering of equations are consistent throughout your manuscript. References to the equations should be as Eq. (1). Make the number of an equation flush-right. For example:

First condition



Figure 4. Heavy soiling

Second condition



Figure 5. Heavy-moderate soiling

Third condition



Figure 6. Moderate soiling

Fourth condition



Figure 7. Light soiling

Fifth condition



Figure 8. Very light soiling

Sixth condition



Figure 9. Cleanest condition

## 5.2 Cleanliness and relative efficiency evaluation

Maintaining the cleanliness of solar PV is one of the most effective ways to protect investment. Soiling the accumulation of dust, dirt and bird droppings can cause immediate and measurable drops in energy production, in solar energy, the relationship between cleanliness and efficiency is governed by the Soiling Rate. As illustrated in Table 1, there is a direct correlation between the Cleanliness levels and the overall Condition Description of the PV modules. The data demonstrates that as soiling levels increases, the cleanliness of the module shifts from (60-97) %. Prolonged poor cleanliness is shown to accelerate physical degradation, such as the formation of hotspots and ribbon corrosion, which ultimately worsens the module's structural condition.

Table 1. Summary of cleanliness and relative efficiency

Rank	Condition Description	Cleanliness (%)	Notes
1	Heavy soiling	60 - 70	Dense dust layer, severe obstruction
2	Heavy-moderate soiling	70 - 75	Surface partially exposed
3	Moderate soiling	75 - 78	Dust has been reduced across major portions
4	Light soiling	78 - 82	Minor patches remaining
5	Very light soiling	82 - 90	Clean the surface of any small residual marks
6	Cleanest condition	90 - 97	Best achieved performance

The overall efficiency recovery attained by the cleaning robot can be analyzed by establishing bounds to the states of having the worst and best cleaning operations:

$$\Delta\eta = (90 - 97) \% - (60 - 70) \% = (20 - 37) \% \quad (2)$$

This recovery band fits adequately the range of previous experimental studies concerning PV cleaning in dusty and arid zones, which reported recovery of 20 to 40% of the lost PV output.

There were also observable incremental improvements in the range of 2 to 6% efficiency increase per PV cleaning degradation state, which shows the value of even partial cleaning to the PV performance.

## 6. CONCLUSIONS

This study assessed the impact that an Arduino-based circular cleaning robot can have on the loss of performance on solar PV panels due to dust. It was shown that the accumulation of dust can cause PV to decrease in efficiency to around 60 to 70%. Robotic dry cleaning, however, can increase that to a performance efficiency of 90 to 97%; an increase of 20 to 37 percentage points. The results of this study suggest that in no water situations, robot vacuums cleaner device can have a significant impact on keeping PV performance metrics due to the high dust. Also, the ease of use, low cost, and efficient performance of the system make it a great impact on small to medium-sized PV systems.

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