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Research article

Development of a Dust Cleaning Robot Controlled using Arduino Microcontroller for Solar Photovoltaic Panel Maintenance

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Abstract: The electricity production of solar photovoltaic (PV) panels often decreases over time due to dust accumulation. Thus, regular cleaning is necessary to maintain optimal electricity production efficiency. Advanced cleaning technologies are commonly used in commercial solar farms. However, household solar PV systems may face challenges in adopting such technologies due to budget constraints or cost-effectiveness considerations. In this work, a low-cost dust-cleaning robot for solar PV panel cleaning systems, utilizing Arduino microcontrollers, was developed. The robot's performance was tested under natural climate conditions, and satisfactory results were demonstrated in removing dust from solar PV panels to sustain electricity generation. This innovation system effectively addresses household solar PV systems' dust accumulation and maintenance issues.

Keywords: Solar photovoltaic panels; Dust cleaning robot; Arduino microcontroller.

1. Introduction

The energy crisis is one of the most critical global challenges due to rapid population growth. However, using conventional fossil fuels harms the environment and humans. Over the past decade, there has been increasing anticipation that sustainable power sources can meet energy demands [1]. Wind, biomass, hydroelectric power, and solar photovoltaics (PVs) are abundant renewable energy sources that are naturally occurring. Photovoltaic systems convert sunlight directly into electrical energy and offer a promising and environmentally friendly alternative to traditional fuel-based power generation. The performance of PV panels is substantially affected by various environmental factors, including wind, ambient temperature, humidity, season, and dust. Dust accumulation on solar PV panels significantly impacts their performance by obstructing sunlight, reducing light intensity for light-electricity conversion [2]. Moreover, this obstruction can cause irregular shading, leading to hot spots that further reduce power conversion efficiency and potentially damage the PVs.

Additionally, the retained heat from dust might increase the temperature of PV panels, intensifying efficiency losses. Dust composition can also chemically

degrade the panel surface. The economic impact includes higher maintenance costs due to frequent cleaning needs, especially in arid and polluted regions, affecting the overall return on investment. Effective mitigation strategies, such as anti-soiling coatings and automated cleaning systems, are essential for maintaining solar PV systems' optimal performance and efficiency in dust-prone environments. Tarigan [3] reported that regular manual cleaning of PV panels can maintain energy output levels that are more than 8% higher annually than those of not cleaned panels. This investigation highlights the significant effect of dust accumulation on PV system performance. Specifically, PV panels not cleaned for 25-30 days experienced a substantial drop in energy output. Pedersen et al. [4] found that the accumulation of sediments, including dust and dirt particles, reduced light transmission by approximately 2.8% for every 10 mg/m² of sediment. Urrejola and Antonanzasc [5] demonstrated a daily decrease in efficiency of 0.13-0.56% for PV panels installed in highly polluted areas due to dust accumulation, with annual degradation recorded at around 1.29-2.77% depending on the PV type. Cleaning every 45 days was identified as the optimal frequency for maintaining PV performance. However, these strategies are often unsuitable for household solar PV panels due to their high costs, inflexibility, complexity, and lack of availability for small-scale applications. A dust cleaning robot provides more advanced features than traditional manual cleaning methods to ensure the system functions correctly. In addition, maintenance can be flexibly scheduled without concern for labor and cost, resulting in high power production rates and low maintenance costs for solar PV panels [6]. Thus, this work presents the development of a low-cost, flexible, and simple maintenance system for a dust-cleaning robot controlled by an Arduino microcontroller for common users. The development design is based on simple operation, low cost, and user flexibility.

2. Materials and Methods

The intensity of incident light that passes through the glass surface to the P-N junction of PVs is important for electricity generation. To investigate the effect of dust accumulation on light intensity, glass slides were used as substitutes for solar PV panel surfaces to represent the surfaces of solar PV panels. These glass slides were exposed to outdoor conditions for 1 to 28 days. After exposure, the slides were evaluated to measure the light intensity passing through them and the mass of the accumulated dust. This assessment used a 1,000 W/m² solar simulator to quantify the reduced transmitted light due to dust coverage. The dust mass was also measured to determine its correlation with the degree of shading observed. This preliminary experiment aimed to determine the effect of dust on shading and its subsequent impact on light transmission. For the solar PV panel, varying amounts of dust (50 mL, 100 mL, and 150 mL) were intentionally dispersed on the PV panel surfaces to simulate different levels of dust accumulation. The simulated incident light was generated by LED spotlights (100 W, 8 lamps) and natural sunlight irradiation at a power density of 906.4 ± 189.9 W/m², as shown in Figure 1. Note that the LED spotlight testing setup was specifically designed to investigate the effect of dust accumulation on the power output of the solar PV panel. While the setup was conducted without standardized protocols for ensuring irradiance uniformity or temperature control, it served as a practical and controlled environment for the study. The electric power generated by the PV panel was then recorded to evaluate the impact of dust on the power generation performance. This experiment was conducted with the PV panel installed at the Faculty of Engineering, Rajamangala University of Technology Lanna Tak, Tak. After assessing how dust affects power output, a dust cleaning robot was employed to remove the accumulated dust from the PV surfaces, aiming to restore their performance. To ensure reliability and consistency, each condition was repeated three times.

An Arduino microcontroller was used to develop the dust-cleaning robot due to its precise control and automation [7-9]. The design process included creating a comprehensive block diagram to outline the system, and the principal components of the robot were illustrated in Figures 2 and 3. The block diagram illustrates the robot's operating principle for cleaning dust on solar panels. The system offers two modes of operation: a manual mode and an auto mode. The manual mode enables users to operate the robot directly. The robot's movements and cleaning functions, including components like the wheels and brush, are managed by an ESP8266 microcontroller that receives commands from the Blynk application on a smartphone (Figure 4). The robot's acrylic body features rubber wheels and a cleaning brush with wool bristles. In auto mode, the robot navigates using a random walk algorithm and operates both the solenoid valve and brush motor. During the cleaning process, the robot prevents falls or drop-offs using four infrared reflective sensors on the unit's undersides. During the cleaning operation, the auto mode was used to clean the PV panels, ensuring thorough

dust removal and enhancing the panels' efficiency. The cleaning time for each cycle was approximately 1 minute and 50 seconds. The implementation of the robot demonstrated a significant improvement in maintaining the power output of solar PV panels by mitigating the detrimental effects of dust accumulation. This study focused on the effectiveness of auto-cleaning solutions in maintaining the long-term performance of solar energy systems.

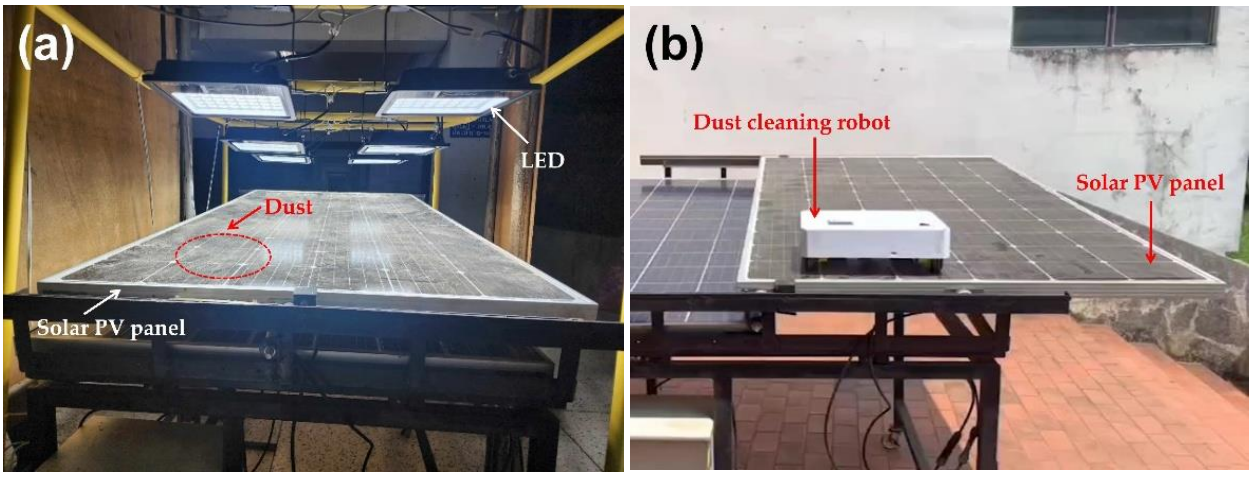

Figure 1. Setup for power output measurement of the 340 W mono-Si PV panel with dimensions of 1956 mm x 992 mm under (a) LED spotlight and (b) natural sunlight.

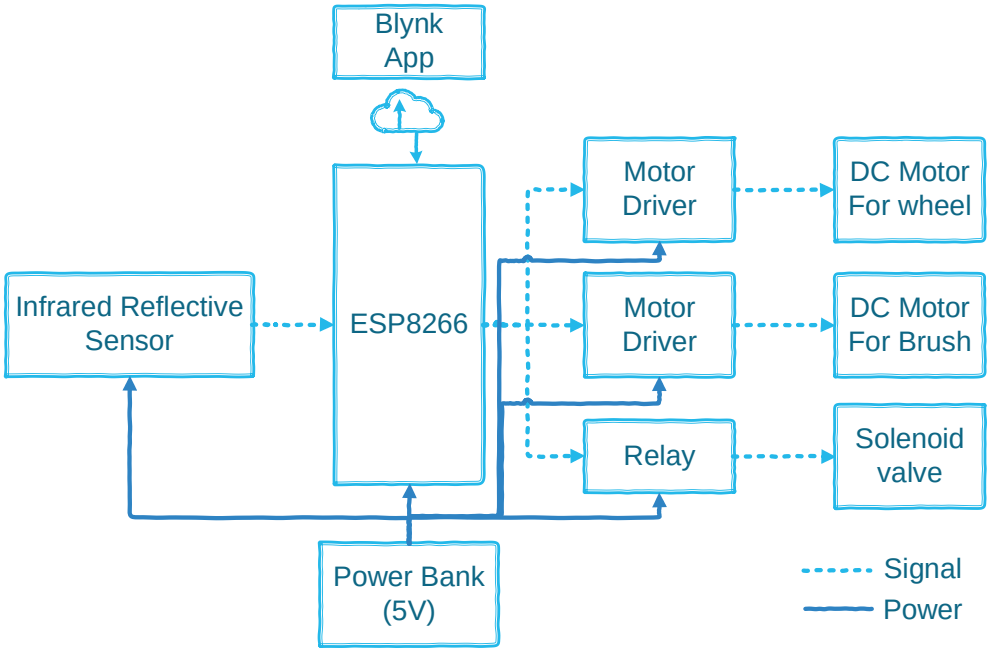

Figure 2. Block diagram of the dust cleaning robot controlled using an Arduino microcontroller.

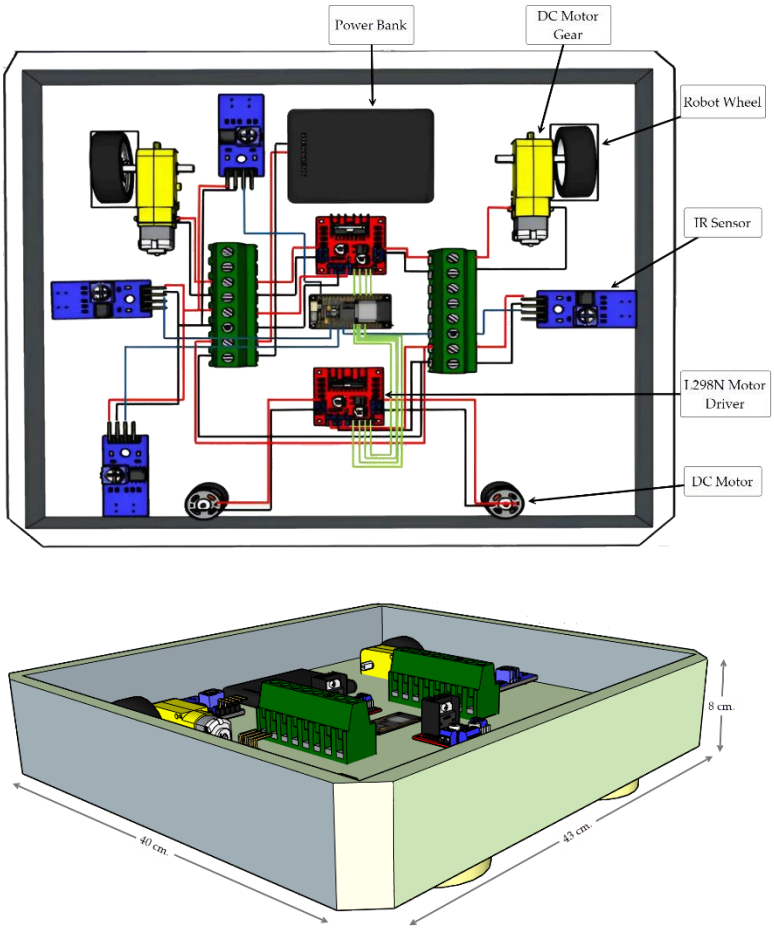

Figure 3. Principal components and 3-dimensional body of the dust cleaning robot.

Figure 4. Screens of the Blynk application on a smartphone are used to control the dust-cleaning robot in both manual and auto mode operations.

3. Results and Discussion

The intensity of sunlight incident on solar PV panels is a key factor affecting electricity generation. It is well known that dust accumulation can significantly reduce sunlight reaching the PV cells. As illustrated in Figure 5, an increase in dust accumulation leads to a corresponding decrease in transmitted light. Specifically, after 28 days of exposure to environmental dust, the transmitted light decreased to 89.13%. This significant reduction can be attributed to dust particles settling on the surface of the PV panels, which obstructs and scatters incident light. This behavior causes a significant reduction in light transmission, negatively affecting electricity generation. Thus, dust accumulation is considered a crucial issue requiring regular cleaning and maintenance of PV panels to ensure optimal performance.

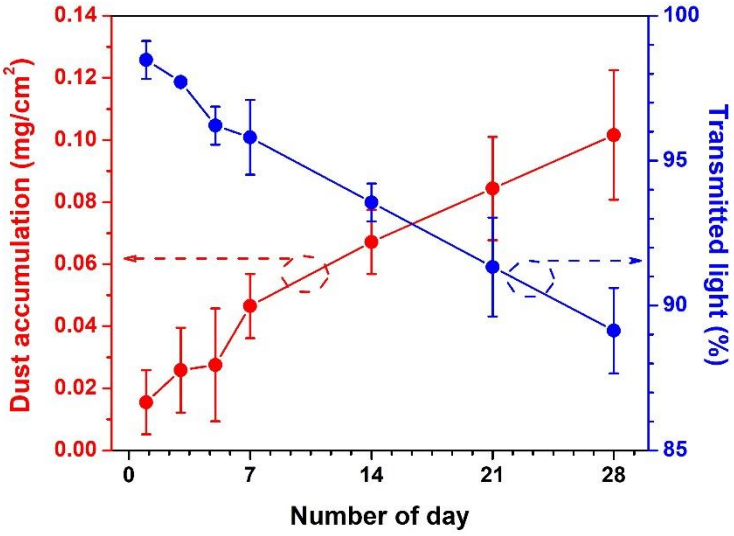

Figure 5. Measurement of dust accumulation and transmitted light.

To investigate the effect of dust accumulation on solar PV panel power generation, the relationship between dust volume and power output was assessed by dispersing three different amounts of dust on the panels and recording the resulting power outputs, as summarized in Figure 6. The investigation was assessed under two conditions: LED spotlight and natural sunlight. Dust volumes of 50 mL, 100 mL, and 150 mL were applied to the PV panel, and the corresponding power outputs were measured. Under the LED spotlight, the power outputs were recorded at 7.90 W, 6.65 W, and 5.64 W for dust volumes of 50 mL, 100 mL, and 150 mL, respectively. Under natural sunlight, the power outputs were 77.32 W, 71.33 W, and 56.61 W for the same dust volumes, respectively. The decrease in power output was observed with increasing dust volume [1,10]. The result indicates a clear inverse relationship between the dust accumulation quantity and the PV panel's power output for both LED and natural sunlight irradiation. As the dust dispersion increased, the power output decreased, implying the negative impact of dust on PV panel efficiency. The results suggest the importance of cleaning panel surfaces from dust accumulation to maintain optimal energy generation. The experiment evaluated the efficacy of the dust-cleaning robot controlled using an Arduino microcontroller in restoring the power output of a dust-accumulated solar PV panel. After cleaning, the power outputs were measured at 10.19 W under the LED spotlight and 85.63 W under natural sunlight. The results indicate a significant improvement in the power output compared to the dust coverage state, demonstrating the effectiveness of the dust cleaning robot in removing surface contaminants. The study suggests the critical role of regular and effective cleaning in maintaining and enhancing PV panel performance, particularly in environments prone to dust accumulation. For comparison with a conventional cleaning by a human, the power outputs of 11.02 W and 89.21 W were measured under LED and sunlight conditions, respectively. The results suggest that human cleaning methods outperform robotic cleaning, but there are few significant differences following observed variability.

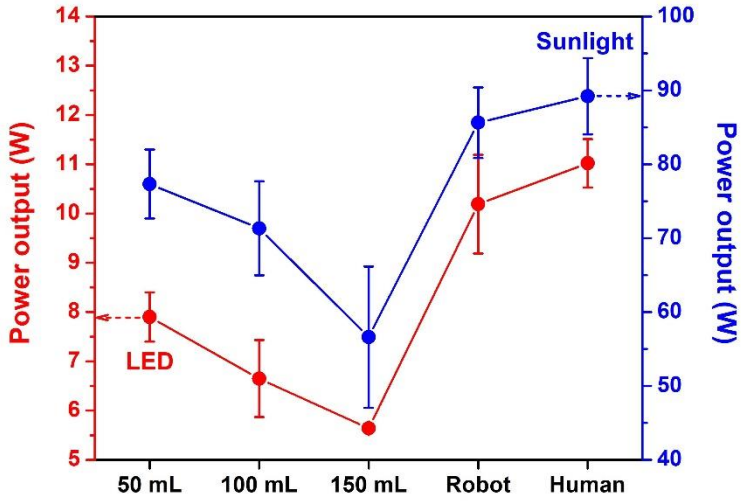

Figure 6. Measure the power output of the PV panel under LED and sunlight irradiation for dust dispersion of 50 mL, 100 mL, and 150 mL after the robot and human cleaning.

4. Conclusions

This demonstration presents the effectiveness of a dust-cleaning robot controlled by an Arduino microcontroller in removing dust and maintaining solar PV panel efficiency. The robot application is a viable solution for mitigating the adverse effects of dust accumulation on solar PV panels. This development can be considered as introducing low-cost robotic technologies into the maintenance routines of solar PV systems, particularly in regions prone to high dust levels, thereby enhancing the overall reliability and performance of solar power installations. Moreover, the developed robot's low cost, effevtiveness, flexibility, and simplicity make it a suitable solution for maintaining household solar PV panels.

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