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Design and Prototype Development of an Arduino-Based Automatic Solar Panel Cleaning Robot

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Abstract**—**Dust, sand, bird droppings and stains that accumulate on photovoltaic (PV) panels reduce the light reaching the cells and therefore the energy the panels deliver, while manual cleaning is slow, costly and hazardous. This paper presents the design and prototype of an automatic solar panel cleaning robot built around an Arduino Uno (ATmega328P) controller. The system consists of a carrier unit that positions it at each panel array and a cleaning unit that sweeps the array with a roller brush and a water spray. Infrared (IR) sensors mark the end of each stage and the units hand over to each other through a wireless signal. DC motors driven through relay and motor-driver stages provide speed and direction control, rubber tracks give grip on the smooth glass, and a small pump supplies water from an on-board tank. In the prototype configuration the system covers three sets of panel arrays, with an 11 ft vertical stroke and a 9 ft horizontal shift, in about 300 s. A first-order energy-balance model and a traction model are derived to show when a cleaning cycle pays off and how the drives can be sized. Advantages, limitations and extensions such as soiling-triggered cleaning, photovoltaic self-powering and remote monitoring are discussed.

Keywords**—***solar photovoltaic, dust soiling, cleaning robot, Arduino, ATmega328P, DC motor, IR sensor, rubber track.*

I. Introduction

Solar photovoltaic (PV) generation is clean, inexhaustible and increasingly cost-competitive, and its installed base has grown quickly. The output of a panel, however, depends on how much light reaches its cells, and the glass surface is continuously soiled by dust, sand, pollen, bird droppings, moss and the stains left by rainwater run-off. Experimental studies show that dust measurably reduces the power of a PV module [1], in-situ measurements show that natural dust deposition can lower the transmittance of PV glass by 20 % within eight days [2], and reviews treat dust as a major loss mechanism in dry, dusty regions [3].

Because panels are tilted, dust, bird droppings and sand that rain does not wash off build up on them, and the energy yields quoted by manufacturers and installers assume clean panels. Regular cleaning therefore protects the investment. Manual cleaning is slow, costly and dangerous, particularly on rooftops, and water-intensive cleaning is impractical at many arid sites. A robot that cleans without a person on the panel addresses these problems.

This paper presents the design and prototype of a low-cost automatic cleaning robot controlled by an Arduino Uno. Its objectives are (i) to remove dust, dirt and debris quickly and effectively so that the panel can capture the maximum energy, (ii) to reduce the cost of manual cleaning and remove the health, safety and environmental risks it carries, and (iii) to limit the wear caused by long-term dirt build-up. Scheduling and supervisory monitoring are treated as extensions. The main contributions are:

(1) a two-unit architecture in which a carrier unit and a cleaning unit are coordinated by an ATmega328P through IR sensing and a wireless hand-over signal;
(2) a hardware design that states the function of each component and the reasoning behind the electrical interface;
(3) a first-order energy-balance and traction model for deciding when a cleaning cycle pays off and for sizing the drives; and
(4) a record of the operating cycle of the prototype together with the advantages, limitations and future extensions of the design.

Section II reviews related work. Sections III to V describe the system, hardware and control logic. Section VI develops the model, Section VII discusses the prototype, Sections VIII and IX cover advantages, limitations and future scope, and Section X concludes.

II. Related Work

Vaghani *et al.* [4] presented an automatic solar panel cleaning system that can be controlled through an application from anywhere. They report about 32 % more energy output than from a dust-covered panel, together with a reduction in the manpower needed for cleaning. Ashtaputre *et al.* [5] describe a low-cost cleaning robot with a separate monitoring system: wireless nodes collect the power output of each panel, cleaning is triggered from this data, panel breakage can be detected, and the information can be reached remotely. Pokharkar *et al.* [6] designed a system that senses dust on the panel and cleans the module with sliding brushes, and they review methods of dust removal. Kulkarni and Kadam [7] also presented an automatic solar panel cleaning system, at a 2018 conference.

Compared with these works, the present design aims at low cost and simple, robust hardware: two units cooperate through IR sensing and a wireless hand-over signal, and an analytical model links the design to the energy it recovers. Table I summarises the comparison.

TABLE I
COMPARISON WITH RELATED CLEANING SYSTEMS

Work	Approach	Reported feature
[4]	Automatic cleaning, application-controlled	About 32 % more energy than a dusty panel
[5]	Cleaning robot with wireless per-panel monitoring	Output-triggered cleaning; breakage detection
[6]	Dust sensing with sliding brushes	Automatic cleaning of the module
This work	Arduino; IR-guided carrier and cleaning units; brush and spray	Low cost; wireless hand-over; energy and traction model

III. SYSTEM DESCRIPTION

A. Overview

The robot consists of two cooperating units. The *carrier unit* shifts the system from one panel array to the next. The *cleaning unit* sweeps the array with a roller brush while a pump supplies water from an on-board tank to a spray nozzle. Both units are driven by DC motors, rubber caterpillar tracks give the robot grip on the smooth, inclined glass surface, and a wireless link allows remote operation. An ATmega328P on an Arduino Uno board is the controller. Besides large solar plants, the design suits smaller installations such as rooftop panels in homes and offices.

Fig. 1 shows the block diagram. The controller receives signals from the IR sensors and from the RF link, and is powered from the supply. Through relay and motor-driver stages it drives the travel and shift motors, the brush motor and the pump with its spray valve, which together act on the PV panel.

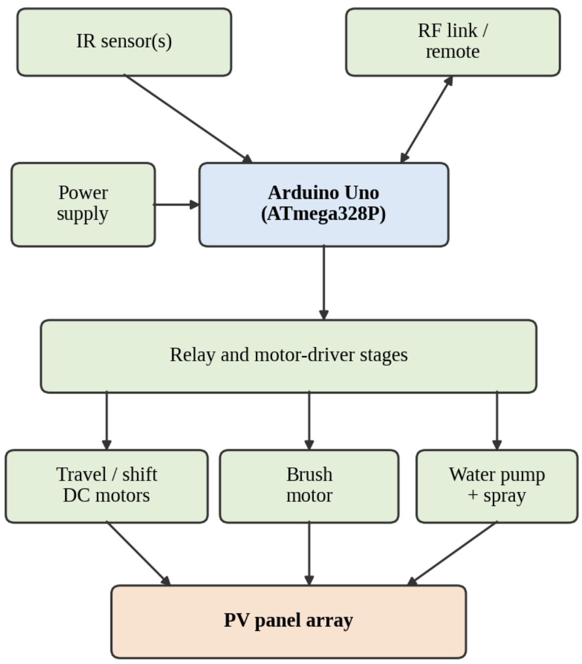

Fig. 1. Block diagram of the solar panel cleaning robot.

B. Operating Principle

The operating sequence is shown in Fig. 2. The IR sensor is read continuously. While its output is LOW, the carrier unit runs and the cleaning unit stays off. When the output goes HIGH, indicating that the sensor has detected its target, the carrier unit stops and a transmitter signal switches the cleaning unit on. The cleaning unit then sweeps the array with brush and spray while the IR sensor is polled again; when the sensor goes HIGH at the end of the sweep, a signal is sent back to the carrier unit, which moves on to the next array. The sequence repeats until all arrays have been cleaned.

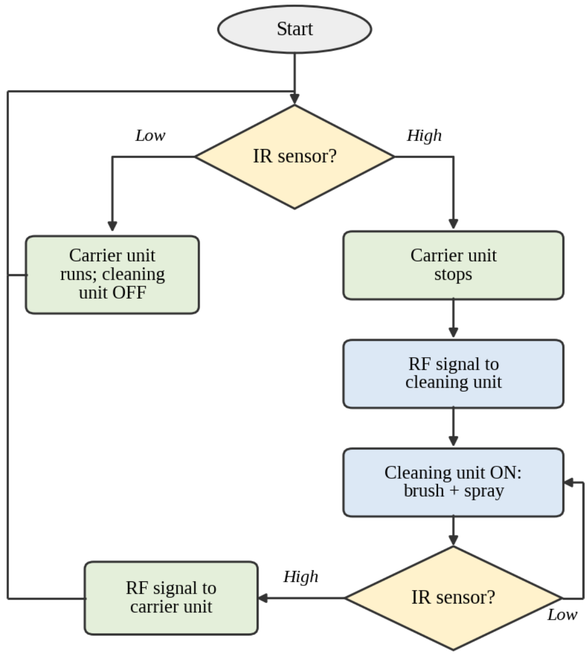

Fig. 2. Operating sequence of the carrier and cleaning units.

C. Operating Cycle

The frame carrying the cleaning brush moves along the length of the panel over a vertical stroke of 11 ft (about 3.35 m) and back. DC motors produce the rotary motion, which is converted to linear motion by a rack-type drive. Gear motors shift the frame horizontally by 9 ft (about 2.74 m), so that three sets of panel arrays are cleaned, and the complete cleaning action, including movement in both directions, takes about 300 s. When one array is finished, the system moves to the next and the process repeats. Table II and Fig. 3 summarise these values.

TABLE II
OPERATING PARAMETERS OF THE PROTOTYPE

Parameter	Value
Vertical stroke along panel	11 ft (≈ 3.35 m)
Horizontal shift between arrays	9 ft (≈ 2.74 m)
Panel array sets cleaned	3
Cleaning time (both movements)	≈ 300 s
Controller	ATmega328P (Arduino Uno)
Cleaning means	Roller brush + water spray

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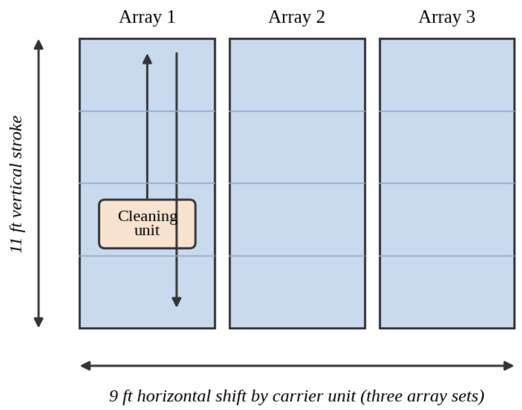

Fig. 3. Schematic of the operating cycle (not to scale).

D. Installation Considerations

Before installation the level of dust, pollen and bird droppings at the site should be assessed, the availability of water identified if spray cleaning is used, easy access for maintenance ensured, and the supporting structure checked for the extra weight. The cleaning mechanism (brush, spray or robot) and the degree of automation are then chosen, the system is integrated with the panel mounting structure using weather-resistant materials, and provision is made for plumbing, an adequate power supply and control. After installation the mechanical parts (brushes, tracks, nozzles) are attached, the electrical connections are made, the controller is programmed and the sensors are calibrated. Initial tests, adjustments and scheduled inspections keep the system in working order.

IV. Hardware Design

A. Controller

The controller is an Arduino Uno based on the ATmega328P microcontroller [8], [9]. The board operates at 5 V, accepts an input supply of 7–12 V (recommended; 6–20 V limit) and provides 14 digital I/O pins, of which six can generate PWM outputs, and six analog inputs. The PWM pins allow motor speed control; the other digital pins carry the sensor inputs and the direction and enable signals. Each I/O pin can source only about 20 mA [8], far less than a DC motor or pump draws, so every actuator is switched through a relay or driver stage.

B. Actuation and Drive

DC motors suit battery-powered mobile robots because their speed and direction are easy to control. In the prototype the DC motors are controlled through both relays and motor drivers, which provide speed and direction control, and the control code for the motors and the water pump runs on the Arduino. Gear motors shift the frame between arrays, and a rack-type drive converts motor rotation into linear travel along the panel.

C. Chassis, Wheels and Tracks

The robot chassis is the structural framework that carries the motors, wheels, sensors and control electronics. Its design must consider the material (aluminium, steel, plastic or composite), size and weight distribution for stability, mounting points for the components, durability under mechanical stress and weather, and modularity for maintenance and upgrades. Wheels determine the movement and stability of a mobile robot. Continuous rubber tracks are chosen here because their large contact area spreads the robot's weight and gives grip on the slick, inclined glass surface.

D. Cleaning Subsystem

A roller brush with an electrostatic cloth wipes the dust from the glass, and a water spray loosens and rinses stuck deposits. A small DC pump draws water from the on-board tank and delivers it through tubing to the nozzle. Diaphragm pumps suit higher pressures, peristaltic pumps give precise dosing, and centrifugal pumps move large volumes at low pressure; for a compact robot spraying a thin film, a small low-pressure pump is sufficient.

E. Sensing, Communication and Power

IR sensors detect the end positions that trigger each hand-over, and an RF transmitter–receiver pair carries the start and stop signals between the units and allows manual remote operation. The prototype draws its power from an electric supply rather than from the PV panels, which adds a running cost that is quantified in Section VI. Table III lists the components and their functions.

TABLE III
MAIN COMPONENTS AND THEIR FUNCTIONS

Component	Function
Robotic chassis	Carries motors, wheels, sensors and electronics
Arduino Uno	ATmega328P controller; runs the control logic
DC / gear motors	Drive the units, the brush and the shifting
Wheels	Support and movement of the carrier unit
Rubber tracks	Grip and load spreading on the glass
Pump motor, tank, piping	Deliver water to the spray nozzle
Controller circuitry	Relays and drivers for motors and pump
IR sensor	Detects end positions for hand-over
RF transmitter / remote	Wireless signals and manual control

V. Control Logic

The control program is written in the Arduino IDE and implements the sequence of Fig. 2 as a three-state machine. In the *positioning* state the carrier motors run and the cleaning unit is off; the IR input is polled and a HIGH level moves the machine to the next state. In the *cleaning* state the carrier is stopped, the brush motor, pump and travel motors of the cleaning unit are enabled, and the IR input is polled until the end of the sweep. In the *hand-over* state the cleaning unit is switched off and a signal is sent to the carrier unit, after which the machine returns to positioning. Motor speed is set with PWM and direction through the driver inputs, and the pump is switched by a relay. Recommended safeguards are to stop all motors if the wireless signal is lost, to add end-stop switches as a back-up to the IR sensors, and to disable the pump when the tank is empty.

VI. Modelling and Analysis

A. Soiling Loss and Energy Recovery

Let P_c be the power of a clean array and P_s that of the same array when soiled under identical irradiance. The soiling loss ratio is

$$S = 1 - P_s / P_c \tag{1}$$

If the mean loss ratio over the interval T (in days) between cleanings is S_m, and E_c is the daily energy of the clean array, the energy lost to soiling is

$$E_{loss} = S_m \cdot E_c \cdot T \tag{2}$$

B. Cleaning Energy and Break-Even Condition

A cleaning cycle of duration t consumes the electrical energy of the brush and drive motors and the pump. With mean powers P_m and P_p over times t_m and t_p (in seconds), the energy per cycle in kWh is

$$E_{clean} = (P_m t_m + P_p t_p) / (3.6 \times 10^6) \tag{3}$$

Because the robot is powered externally, cleaning is worthwhile in energy terms only if

$$S_m \cdot E_c \cdot T > E_{clean} \tag{4}$$

Cost terms (water, brush replacement, amortisation of the robot) are then subtracted from the value of the recovered energy. Equation (4) shows why the cleaning interval T should be set from measured soiling rather than from a fixed calendar, and why a lightweight robot with a short cycle, such as the 300 s of the prototype, is favourable.

C. Traction on the Inclined Panel

For a panel tilted at angle θ, a robot of mass m rests without sliding if the friction coefficient between track and glass satisfies

$$\mu \geq \tan \theta \tag{5}$$

For example, a tilt of 30° requires $\mu \geq 0.58$. Water films lower μ, which is a further reason for wide rubber tracks. Moving along the slope requires a tractive force

$$F = m\, g\, (\sin \theta + c_r \cos \theta) \tag{6}$$

where c_r is the rolling-resistance coefficient. With sprocket radius r, gear ratio n and drive efficiency η, each drive motor must deliver a torque of at least $F\, r / (n\, \eta)$ per driven sprocket, divided among the driven sprockets.

D. Electrical Sizing

The supply current is the sum of the motor, pump and controller currents, with motor starting currents considered. If the robot is battery-powered, the number of cycles per charge is E_{batt} / E_{cycle}, which gives a direct link between battery size and the number of arrays that can be cleaned. Since the Arduino pins supply only about 20 mA, relay coils or driver inputs are used as buffers.

VII. Prototype and Discussion

The prototype was built with the components of Table III, and control code for the DC motors and the water pump was written and implemented on the Arduino. The prototype operated as planned, cleaning the panel arrays through the sequence of Fig. 2 in about 300 s for the arrangement of Table II. Instrumented energy and cleaning-quality measurements were not part of this work, so no quantitative performance figures are claimed.

The following measurements are needed to complete the evaluation: (i) the I–V characteristic and maximum power of a soiled array before and after cleaning, from which S in (1) follows; (ii) the mean power and duration of the motors and pump, to obtain E_{clean} in (3); (iii) the water used per cycle; and (iv) the fraction of the panel area cleaned and the cleaning quality for different dust types. With these data, (4) can be evaluated for the installation and the cleaning interval optimised.

VIII. Advantages and Limitations

Advantages. The cost of production is low and no heavy machinery is needed. The robot removes the risk to workers on the panels and needs no manual assistance. The working principle is simple, the unit is portable, and it is easy to construct and low in maintenance. As an autonomous mechanism it can be attached to panels and operated without a person.

Limitations. The electrostatic-cloth roller brush has to be replaced from time to time. Larger installations need a scaled-up design, for example higher motor torque. The system is powered from an external supply, not from the PV cells, so it adds a running cost. It is less effective on sticky dust and at panel corners, where a harder brush or mopping action is needed.

IX. Future Scope

The design can be extended in several ways: (i) surface vacuum cleaning and improved water spray; (ii) dust and light sensors, or monitoring of panel output as in [5], to trigger cleaning only when needed; (iii) silicone brushes for longer cleaning life; (iv) belt drives in place of the rack system; (v) more capable microcontrollers instead of the Arduino Uno; (vi) remote-controller and IoT or SCADA-based supervision with cleaning schedules; and (vii) a battery charged from the PV array so that the robot is self-powered.

X. Conclusion

This paper presented the design of an Arduino-based automatic solar panel cleaning robot in which a carrier unit and a cleaning unit cooperate through IR sensing and wireless hand-over. DC motors controlled through relays and motor drivers give speed and direction control, and a brush and water spray remove dust from the panel. The prototype cycle covers three panel arrays in about 300 s. The energy-balance and traction models give a rational basis for choosing the cleaning interval and sizing the drives. The next step is an instrumented field trial to quantify the recovered energy, cleaning energy and water use.

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