Towards Autonomous Cleaning of Photovoltaic Modules: Design and Realization of a Robotic Cleaner

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***Abstract* — Solar panels typically consist of photovoltaic (PV) cells covered by a protective glass coating, which generate electricity when subjected to radiations. However, the capability of electricity generation is constrained due to layer of dust on PV modules. In contrast with conventional method of cleaning the modules using water, this paper presents design and development of a robotic cleaner for cleaning PV modules of Quaid-e-Azam Solar Park (QASP). The hardware as well as software architectures of the proposed robotic cleaner are detailed. The novelty of the design lies in its low cost indigenous development and simplicity in design. The mechanism primarily consists of ducted fan, roller brush and blower fan to offer slippage-free motion and cleaning on a glassy surface. Series of experiments and field trials demonstrate efficiency of the mechanism in cleaning the modules effectively.**

Keywords—Robotic cleaner, Solar energy, Photvoltaics, Dry cleaning, Improving electricity yield

I. INTRODUCTION

Advances in the domain of mechatronics have broadened the application horizon of robots [1]. Nowadays, robots can be extensively seen in areas like haptics [2], rehabilitation [3], motion assistance [4], cognition [5], nuclear power plants [6], space [7], industry [8] [9], food sector [10] and so on. This paper explores applications of robots in renewable energy resources [11].

Solar panels typically consist of photovoltaic (PV) cells covered with a protective glass coating. Subject to sufficient amount of solar radiations falling over them, they absorb the energy from the radiations and subsequently convert this energy into electricity. Solar cells form 'green energy' resources since they reduce carbon dioxide emissions and hence protect the surrounding environment.

Solar energy completely depends on the light and radiations coming from the sun. If the light and radiations are greater, the energy produced by PV modules is also greater [12]. So developing a solar power plant requires large area so as to give maximum exposure to the light and radiations. Weather also plays a critical role to generate energy from solar cells [13]. A cloudy and foggy weather leads to little room of exposure of radiations from sun thereby harnessing very less amount of electrical energy from PV modules. Considering the aforementioned factors, the most appropriate place for the large solar plants is the deserts, where the weather is very hot and high level of light and solar radiations are readily available. Also, there are relatively less chances for the weather to change in deserts.

Given an ideal place for harnessing solar energy, the world largest solar power plant i.e. Quaid-e-Azam Solar Park (QASP) has been developed in Cholistan desert. Fig. 1 illustrates QASP field consisting mainly of an array of PV modules. The current setup can generate up to 400MW of energy and is estimated to produce 1000 MW by the end of 2018. It, however, suffers from problem of dirt and sand [14]. This is primarily due to high probability of occurrence of Dust Storms (DS) in Cholistan region which results in deposition of layer of dirt and sand on solar modules [15]. This layer then blocks incoming radiation from sun to fall on PV modules [16, 17] ultimately resulting in low production of energy [18-21].

Fig. 1. PV modules located at QASP site.

The variation of DS over a time span of a decade is evident from Fig. 2 where DS frequency in Cholistan and surrounding areas is illustrated. Cumulative number of DS days can annually go beyond one month, highlighting the importance of cleaning mechanism for PV modules.

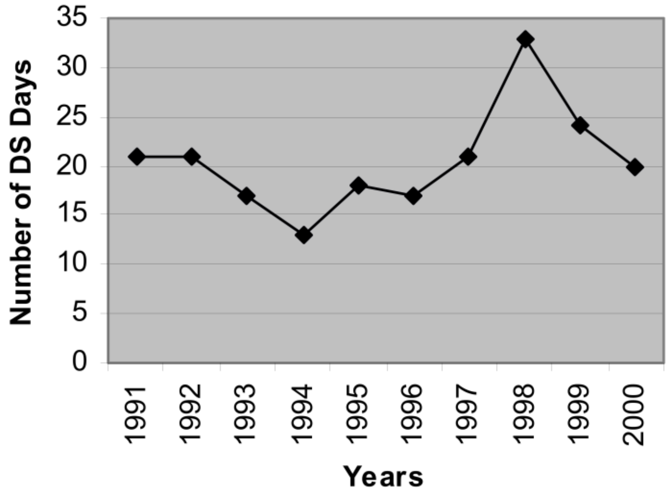

Fig. 2. Typical variation of DS from 1991 - 2000 [22].

Cleaning of PV modules is required regularly for better energy production and efficiency. At present, cleaning of the modules is done using water tanks. This traditional method of cleaning leads to excessive emission amount of carbon dioxide due to burning of fuel during the process of water transportation from reservoirs to PV area [23, 24]. Traditional cleaning also demands high laborious work and high amount of water, which indirectly increase the overall operational cost. Additionally, high amount of water is wasted in this process. Distilled water also affects the efficiency of PV modules [25]. Therefore, there is an increasing belief that robotics based solutions facilitate cleaning of PV modules and may replace traditional methods in near future.

This paper presents the design and implementation of a robotic cleaner for dry cleaning of PV modules. The remaining paper is organized as follows; Section II briefly outlines field study and the proposed platform. Section III presents design details while experimental results are depicted in Section IV. Finally Section V concludes the paper.

II. Field Study

As shown in Fig. 1, PV area consists of several rows of PV modules. These modules are oriented at an angle of 25° to enhance harnessing of solar energy as illustrated in Fig. 3. The upper side of the PV modules consists of a layer of transparent glass that protects solar cells from water and other external effects. This protective glass and angle of inclination of a PV module offers constraints in locomotion of robotic cleaner. The angle of inclination and smooth surface lead to the robot slippage during its motion. Moreover, continuous falling of dust on the protective glass embeds layer of dirt that needs to be scratched first with a brush for proper cleaning.

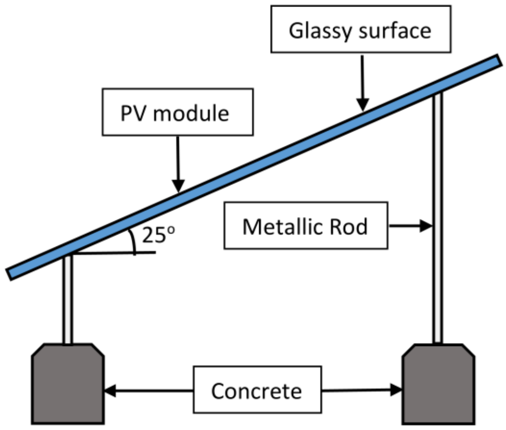

Fig. 3. Schematic of PV module elivated at an angle of 25º.

III. Robot Base and Structure

The robotic cleaner has been designed keeping in view structure of the modules and associated orientation, in such a way that the robot can perform locomotion easily on PV modules even at angles greater than 25° without any slippage and error. The design contains a roller brush for the scratching of dust from the PV module, a ducted fan which creates adhesion towards PV module to avoid slippage, four differential drive motors and four running wheels for its smooth locomotion and a blower fan to remove the dust from PV modules. Fig. 4 shows the schematic of the proposed design.

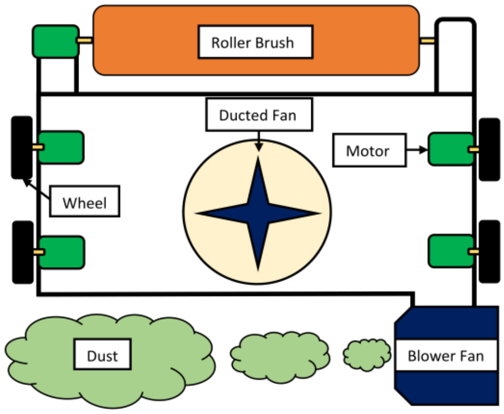

Fig. 4. Schematics of the proposed robotic cleaner design.

Based on the proposed design, a prototype of the robotic cleaner has been fabricated in-house. Fig. 5 illustrates the prototype. Where placement of various prominent components can be clearly seen. The control algorithm resides in the controller while an on-board battery meets power requirements of the system.

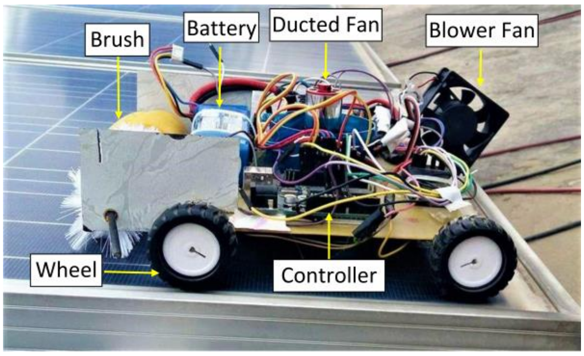

Fig. 5. Fabricated prototype of the proposed robotic cleaner.

IV. Design Details

The design of the robotic cleaner follows modular approach which offers high degree of flexibility and fault tolerance at a low cost and mass [26, 27]. The proposed design of the robotic cleaner consists of nine separate modules that implements various operations like locomotion, sensing, data processing and cleaning. Fig. 6 illustrates higher-level block diagram of the robotic cleaner.

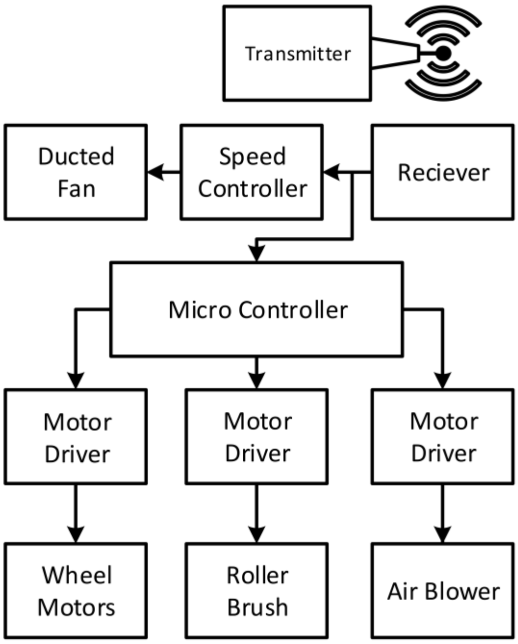

Fig. 6. Higher level block diagram of the robotic cleaner.

A. Ducted Fan

Locomotion constraints arising from slippage due to traversal on smooth surface and inclination of PV modules are handled by use of ducted fan and runner wheels.

Ducted fan creates adhesion, which lets the robotic cleaner stuck to PV module thus mitigating the effect of slippage. Ducted fan moves in counterclockwise direction and creates a negative air pressure. This pressure compresses the air so as to flow it out at a high speed ultimately resulting into thrust and thus creating adhesion towards PV module. The designed mechanism permits the robotic cleaner to move on inclined PV modules conveniently and without encountering any slippage.

B. Speed Controller

This controller is designed to change speed of the ducted fan motor in accordance with the received input to control speed of the ducted fan for proper adhesion. The controller receives signal from transmitter throttle channel and consequently varies speed of ducted fan to regulate the thrust accordingly.

C. Receiver and Transmitter

A three channel transceiver is used to control the robot wirelessly First channel sends the rotation commands through which the robot decides rotational direction. Second channel is used to command forward and backward movement of the robot while the last channel sends the throttle signal to the speed controller to regulate the speed of the ducted fan.

D. Microcontroller

Microcontroller is the main processing unit, which interacts with other modules of the proposed system , gives instruction signal and reads the sensors data to determine corresponding decisions [28]. In the present work, the receiver receives the transmitted signal and sends it to 'Arduino Uno' where it is analyzed and decoded. Microcontroller then makes the decision, starts the corresponding module and controls its operations.

E. Motor Driver (H Bridge)

The current provided by the microcontroller is insufficient to drive motors and fans, also it is unable to change the direction of rotation of the motors i.e. clockwise and anticlockwise rotation without using additional circuitry. So motor driver is used which allows motors to draw high current for its operations [29]. It works based on the control signal generated by the microcontroller and is responsible for changing the direction of rotation of motors by changing the polarity of provided power signal across the voltage terminals of the motors.

F. Roller Brush and Blower Fan

Roller brush performs the key operation in the robotic cleaner. With the passage of time, dust starts to stick on PV modules ultimately resulting into formation of a thick layer of dust on the modules. This phenomena leads to reduced power yield by the modules since dust resists exposure of radiations on the solar cells. Roller brush in the proposed system scratches dust from PV modules and allows blower fan to remove this dust by providing a strong thrust of blowing air. The strong thrust of blowing air takes away the dust and other particles from PV modules and makes the glassy surface shinny and clear.

G. Wheels and Motors

As the robotic cleaner needs to climb PV modules inclined at 25°, the weight of the robot should be kept to minimum so as to decrease the effect of gravitational force. The slippage of robot wheels due to shinny protection glass of PV modules is reduced by using rubber wheels along with the ducted fan. These wheels cause the robot to maintain its excellent grip.

V. Software Architecture

Initially, the receiver receives the signal from the transmitter. This signal is then feed to one of the three processes depending upon the type of the signal received. The first process controls forward and backward movements of the robot. It takes decision based on the received signal and resultantly moves the robot in the commanded direction. The second process controls the robot's rotation. Following this process, the angle of rotation is read and the robot rotates towards right or left corresponding to the signal received. The third process controls the adhesion of ducted fan and it starts and stops the operation of roller brush and air blower. Fig. 7 illustrates complete description of software architecture for the robotic cleaner in a systematic manner.

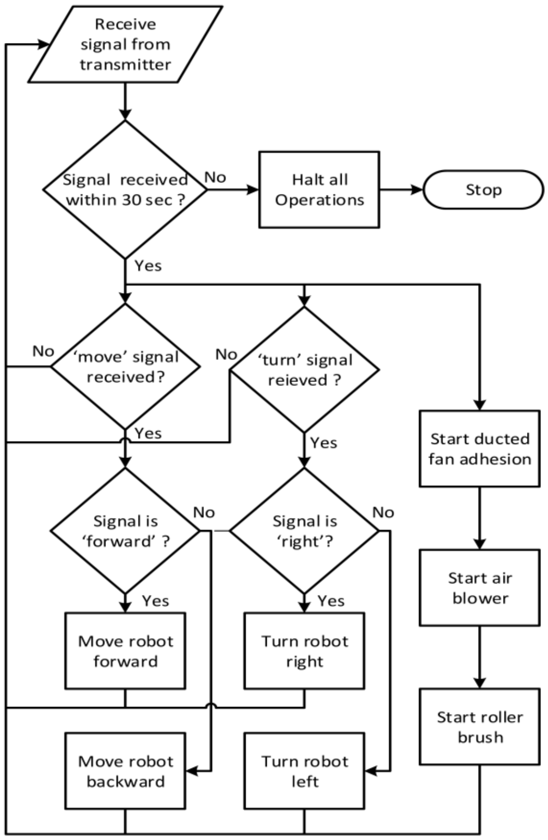

Fig. 7. Software architecture for the proposed robotic cleaner.

VI. Results

The fabricated prototype of the proposed robotic cleaner has been then subjected to analysis. Fig. 8 illustrates the radiation plot illustrating accumulated directional radiations coming from the sun. The electrical energy produced by PV modules is a direct function of amount of radiations falling on the modules as reported in [30].

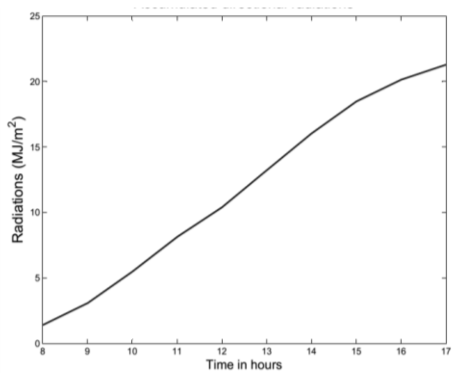

Fig. 8. Accumulated directional radiations on PV modules.

The maximum power generation of PV modules of 100MW has been calculated in (1) by measuring maximum voltage and maximum current of the modules using an advanced SCADA control system. The efficiency factor of the plates can be calculated using (2) [31].

$$P_{max} = V_{max} * I_{max} \quad (1)$$

$$\text{Efficiency } (\eta m) = P_{max} / P_r \quad (2)$$

Where,

P_{max} = Maximum operating power

I_{max} = Maximum operating current

V_{max} = Maximum operating voltage

P_r = Solar power radiation = Irradiance * Total area

The maximum power generated by the modules while they are dirty is plotted in Fig. 9. Continuous exposure to dust causes PV module to generate lesser amount of power. The modules are then cleaned using the proposed robotic cleaner. As can be seen from the figure, significant increase in power generated from the cleaner modules is observed.

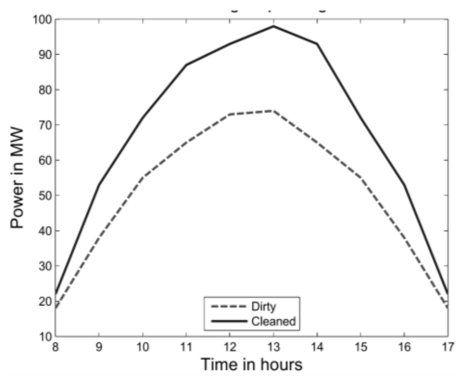

Fig. 9. Impact of cleaning PV modules on power generation.

An operational scenario consisting of the proposed robotic cleaner and PV modules is illustrated in Fig. 10. The roller brush scratches the dust from PV module and then the blower fan blows dust out of module. Interested readers may like to view video of the robot effectively cleaning the modules [32].

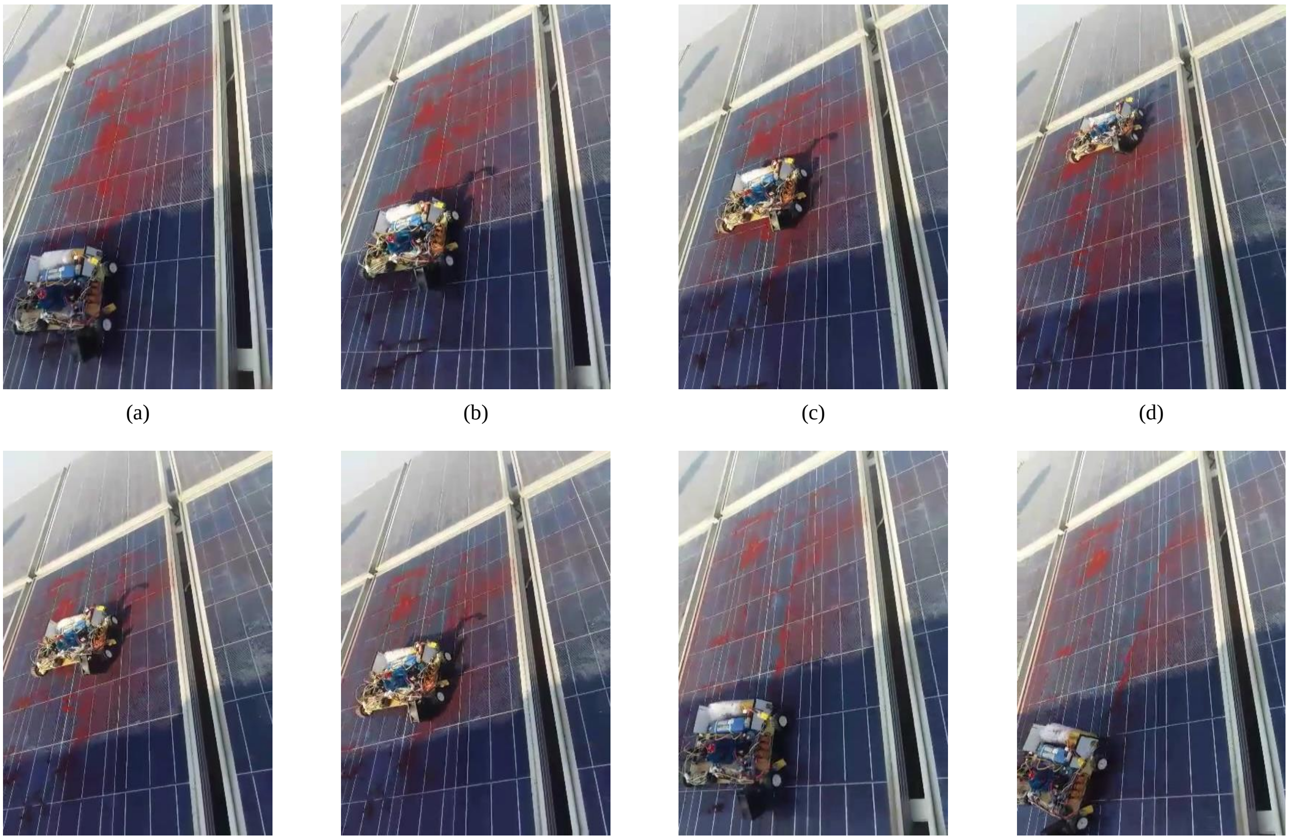

Fig. 10. The robot in operation while cleaning PV module (a) Initialization of the robot (b,c) The robot starts climbing and cleaning the module (d) It reaches at the top of the module (e-g) It starts moving and cleaning downward (h) It reaches at the bottom of the module.

VII. Discussion and Conclusion

This paper presents a robotic system for autonomous cleaning of PV modules. Cleaning using such a robot has a lot of benefits over traditional method of 'water wash' cleaning. Table I illustrates the comparison between these two approaches and depicts enormous potential of employing a robotic cleaner.

TABLE I. Comparison between water wash and robotic wash

Factor	**Factor comparison of water wash and robotic cleaning**	
	Water Wash	***Robotic Cleaning***
Operational cost	High	Low
CO_2 emmisions	High	Nil
Labor cost	High	Nil
Water wastage	High	Nil
Fuel consumption	High	Nil
Air pollution	High	Nil
Human safety	Low	High

In case of 'water wash', transporting water tanks in PV area results in emission of numerous gases creating air pollution. However, solution based on mechatronic systems mitigate CO_2 emissions and helps to save water and fossil fuels for the future. A low-cost prototype of the robotic cleaner has been indigenously designed and fabricated. Table II lists estimated price of major components of the prototype.

TABLE II. Price of the Robotic cleaner

Sr. No.	**Actual price of the robotic cleaner**		
	Item	***Quantity***	***Price (PKR)***
1	Robot structure	-	500
2	Gear motors	5	1000
3	Wheels	4	200
4	Motor driver	2	1200
5	Ducted fan	1	300
6	Air blower	1	150
7	Roller brush	1	200
8	Microcontroller	1	950
9	Battery	1	1000
10	Speed controller	1	2000
	Total (approx.)	-	6000

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