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Design of a Robotic System for Cleaning Solar Panels in Benin

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Abstract

To get the most out of your photovoltaic solar modules, it's essential to clean them to enable them to capture sunlight and produce electricity efficiently. Several solar module cleaning solutions have been developed, but the most recent are solar panel cleaning robots. With this in mind, a robot has been designed, an estimated total cost of 300,000 CFA francs, to optimize the cleaning of photovoltaic solar modules in Benin. The robot is an automated guided vehicle fitted with a roller brush at the front, rotated by a small DC motor. The robot has four (04) wheels coupled to four (04) DC motors, and moves over the PV modules without any risk of damaging them, thanks to the rubber tracks mounted on the wheels to protect them. An infrared remote control activates and moves the robot, rotating the roller brush and sending water through a 12 V mini water pump just before the robot passes over, for optimum cleaning of the photovoltaic solar modules. The system is equipped with a 12 V battery that is progressively charged by a small solar panel attached to the robot, making it self-sufficient. What's more, there's no risk of damaging or scratching the photovoltaic panels during cleaning. What's more, the robot is easily recyclable, offering greater protection for the environment.

Keywords

Solar Photovoltaic, Cleaning Robots, Solar Modules, DC Motor, Water Pump

1. Introduction

The Independence from fossil fuels remains a major challenge facing the energy sector today. That's why Goal 7 of the Sustainable Development Goals (SDGs) aims to guarantee access to clean, affordable energy for all. Photovoltaic solar energy is one of the most popular solutions, especially in Africa, which is considered the continent of the sun, but which is still home to an insignificant number of solar power plants, despite statistics estimating that nearly 645 million Africans have no access to a source of electricity [1]. However, once a solar power plant has been installed, there is also the problem of maintenance and, more specifically, cleaning of the modules making up the solar field. What's more, photovoltaic modules need to capture the sun's rays in order to generate electricity. Dirt on the surface of the modules prevents direct contact with the sun's rays, and influences their efficiency. One of the main causes of degradation in the performance of photovoltaic panels is the accumulation of dust on them. Their performance could be improved by periodic cleaning [2]. It is estimated that dirt on photovoltaic solar modules reduces their efficiency by 7% [3] [4]. To remedy this problem, the cleaning of these solar modules is strongly encouraged. It is advisable to clean panels earlier in the morning than in the evening, to avoid violent temperature shocks with the temperature of the water used, and burns [5]. The cleaning methods used today in Africa, and more specifically in Benin, mostly consist of using a telescopic broom or a soft cloth and water to clean by hand. This method is risky when installed on a house roof, tedious when used on a vast solar field, and tiring when used on a site that is much more exposed to pollution, requiring frequent and regular cleaning. Several methods have been developed to solve this problem, including the use of cleaning vehicles, water-propelling drones and automatic irrigation systems [6]. Furthermore, in areas with low rainfall, using a combination of air jets and brushes could provide a more thorough cleaning than systems using a single method, for panels exposed to a wide variety of dust types [7]. But these solutions are water intensive and/or still rely on fossil fuels, as in the case of fuel-powered cleaning vehicles. In the search for more autonomous and optimal solutions, robotic cleaners are a prospect worth considering.

This study concerns the development of a robot for cleaning photovoltaic solar modules in Benin, ridding them of any dust or dirt that might prevent them from efficiently capturing sunlight to ensure optimal operation.

2. Materials and Methods

In this section, the materials and tools needed to design our robotic system for cleaning photovoltaic solar modules are presented, along with the research methodology and associated dimensioning. The main objective is to design a solar module cleaning robot and to carry out an economic analysis of the robot.

2.1. Materials Used for the Robotic System

The materials and measuring equipment used during the design phase are described below: The ESP32 module is based on an ESPWROOM-32 clocked at 240 MHz, and is capable of operating reliably in an industrial environment, with an operating temperature ranging from 40˚C to 125˚C. It is powered by advanced calibration circuitry and can dynamically remove external circuit imperfections and adapt to changing external conditions [8]. The ESP32 module can be programmed from the Arduino IDE. We've chosen to program the ESP32 module with the Arduino IDE because it's so easy to use.

A microcontroller is an integrated circuit that brings together the essential elements of a computer: processor, read-only and random-access memory, peripheral units and I/O interfaces. Microcontrollers are characterized by a high degree of integration, low power consumption, lower operating speed (from a few megahertz to over a gigahertz) and lower cost than the general-purpose microprocessors used in personal computers [9]. A Bluetooth that enables bidirectional data and file exchange using UHF radio waves in frequency bands between 2.4 GHz and 2.483 GHz [10].

A minimum 8 Ah 12 V battery and a 20 Wp 12 V photovoltaic module were chosen to power the system.

The buck XL4014, 5 A step-down converter takes an input voltage of between 4 V and 36 V DC and outputs an adjustable voltage of between 1.25 V and 36 V DC. It will act as an intermediary between the battery and the ESP 32 module to supply the latter, as the two cannot be directly linked, as this could damage the module.

Four (04) DC motors are used to move the robot. One is a worm gear motor for roller brush rotation, whose rotation can be changed by changing the wiring method. With a nominal voltage of 12 V DC, this motor features self-locking performance, so that the motor output shaft cannot rotate when there is no electricity. The direction of the transmission output shaft is perpendicular to the motor shaft, so it can be used directly in our system without the need for belt clearances.

The L293D motor driver module whose main driver is the L293D integrated circuit chip, a very popular chip when it comes to driving small, low current motors. With one L293D chip, we can control two DC motors or one stepper motor. As the motors cannot be directly coupled to the ESP32 module used for this project, at the risk of damaging it, since the motors need a voltage of 12 V to operate while the ESP32 module only offers 3.3 V at its output, the L293D motor control module is needed to act as a bridge between the microcontroller and the motors. The module therefore facilitates control of the motors by the ESP32 using a suitable external power source. Together with the motors and rubber tracks, the robot's wheels form its feet. They are coupled with the motors, which rotate them to move the robot.

The robot's rubber tracks enable the motor wheels to adhere to the walls of the photovoltaic modules without the risk of damaging them. With rubber tracks, the robot will be able to move easily over the modules without fear of scratches that will contribute to further problems of reduced module performance.

The electronic relay acts as a switch. It is a versatile relay card with isolated inputs. Each of the two channels can conduct up to 10 A and 28 V DC with a 5 V supply voltage for the input signals. The choice of such a module is justified by the fact that it is used for the electric pump and in the control of the battery charge adapted to the system.

The DC electric pump is a mini submersible water pump with a 12 V motor and a thermoplastic body. It delivers water to the panels just before the roller brush is used for cleaning.

The 2.5 m mini hose (7/10 mm) is connected to the water pump as a water supply line.

The roller brush plays the same role as telescopic brooms in the case of manual cleaning. In our system, the roller brush is set in rotation at the same time as the pump is activated, enabling it to clean the photovoltaic modules in contact with the water already delivered by the pump. The brush is attached to the front of the robot. We use a soft roller brush to avoid damaging the photovoltaic modules.

The infrared receiver remote control uses light to send commands between the transmitter and receiver. The diode transmitter emits infrared rays which travel through the air. These signals are then received by a photodiode, which is able to transform the light signal it receives into an electrical signal. This infrared remote control-receiver unit can be used to give instructions for activating or deactivating the water pump, for setting the roller brush in rotation by the motor acting as a roller brush, and for moving the robot from one point to another by controlling the motors to which the robot's wheels are connected.

The Arduino IDE provides a set of essential tools for writing, uploading and debugging programs on Arduino boards.

The voltmeter measures the battery voltage each time, in order to define set-point voltages at which the battery should start charging or stop charging. It's a bridge divider with ohmic conductors for measuring the 0 - 20 V DC range.

A conventional switch is used to switch off or manually switch on our robotic system, as well as electrical wires for wiring and interconnecting the system's various circuits.

A VeroBoard will be used to support the wiring. A 3D printer will also be used to print out part of the robot body, specifically the support to which the roller brush will be attached. For the robot body, plywood is used, as the entire body of the robot, with the exception of the support to which the roller brush will be attached, is made of plywood.

Fusion 360 software to model the various parts that make up the robot body.

Fritzing software facilitates circuit communication, as well as their transformation into production-ready schematics. Objective criteria such as performance, popularity, sizing and availability were followed in the careful selection of these tools and equipment.

2.2. Research Methodology

To achieve the design objective, the methodological approach followed is based on the following steps:

- Drawing up specifications;
- Inventory of materials needed to build the robot;

- Robotic system architecture definition;
- Simulation;
- Assembling the various robot parts;
- System testing and validation.

2.3. Sizing

Four (04) DC motors have been designed to move the robot.

2.3.1. Sizing the DC Motor

For better dimensioning, a specification is necessary to provide information on the preliminary data essential for dimensioning.

In accordance with the specifications, we have: $v = 0.083\ \text{m/s}$ and $m = 5\ \text{kg}$. The wheels chosen have a diameter of $d = 6 \cdot 10^{-2}\ \text{m}$. The robot has four wheels and therefore four motors, *i.e.* $N = 4$. The following considerations also apply to $\alpha = 35˚\text{C}$ and $R = 1$. The next step is to determine the motor's torque Co and power P_m. To do this, the motor speed is obtained by expression (1):

$$\omega = R \times \frac{60 \times v}{\pi \times d} = 26.53\ \text{tr/mm} \tag{1}$$

The forces applying to the robot are the driving force F_m and the weight Po, the reaction of the support being considered zero as it is perpendicular to the direction of motion.

$$Co = \frac{F_m}{4} \times \frac{d}{2} \tag{2}$$

According to the fundamental principle of dynamics, the following expression (3) emerges:

$$F_m - m \cdot g \cdot \sin \alpha = 0 \tag{3}$$

The robot speed is constant and $a = 0\ \text{m/s}^2$. This gives:

$$Co = \frac{m \cdot g \cdot d \cdot \sin \alpha}{8} = 0.21\ \text{N} \cdot \text{m} \tag{4}$$

It comes the expression (5):

$$P_m = Co \times v_m = 5.6\ \text{W} \tag{5}$$

We therefore choose four small DC electric motors for the robot's wheels, each with the following characteristics: Voltage $12\ \text{V}$; motor power $5.6\ \text{W}$; motor torque $0.21\ \text{N} \cdot \text{m}$; angular speed $26.56\ \text{tr/min}$.

A worm gear motor is chosen to rotate the roller brush. This is a wide-range DC motor, whose rotation can be changed by changing the wiring method. With a voltage rating of 12 V DC, this motor features self-locking performance so that the motor output shaft cannot rotate when there is no electricity.

2.3.2. Solar Module and Battery Sizing

Sizing is necessary to select the right power supply for our system. Table 1 below shows the power balance of the components to be considered for sizing.

Table 1. Power balance of the system's electronic components.

<table>
<tr><th colspan="2"></th><th>Number</th><th>Voltage (in V)</th><th>Intensity (in A)</th><th>Power (in W)</th></tr>
<tr><td colspan="2">Model ESP32</td><td>1</td><td>3.3</td><td>1.2</td><td>3.96</td></tr>
<tr><td rowspan="2">Engine</td><td>For roller brushes</td><td>1</td><td>12</td><td>0.14</td><td rowspan="2">24.08</td></tr>
<tr><td>For the wheel</td><td>4</td><td>12</td><td>-</td></tr>
<tr><td colspan="2">Pump</td><td>1</td><td>12</td><td>0.3</td><td>5</td></tr>
</table>

Motor starting power is not taken into account in the power calculation, as we opt for soft-start motor technology.

If P_T is the total power of the circuit and P_{ESP32}, $P_{moteurs}$ and P_{pompe} are the powers of the ESP32 module, motors and pump respectively, the following expression (6) is obtained $P_T = 33.4\ \text{W}$.

$$P_T = P_{ESP32} + P_{moteurs} + P_{pompe} \tag{6}$$

If we consider that cleaning takes place in two (02) hours and we call B the system's energy requirement, we find $B = 66.08\ \text{Wh}$ using the following formula (7):

$$B = 2 \times P_T \tag{7}$$

The peak power P_p of the corresponding panel is obtained equal to $16.94\ \text{Wp}$ from Equation (8) considering the minimum irradiation Ir in Benin which is $3.9\ \text{kwh/m}^2$ per day.

$$P_p = \frac{B}{I_r} \tag{8}$$

This result implies the choice of a 20 Wp 12 V PV module.

As for the choice of the corresponding battery, its capacity C is calculated by formula (9) considering $n = 1$ and $D = 0.7$.

$$C = \frac{B \times n}{U \times D} \tag{9}$$

control module performs the calculations required for the system to operate correctly, based on the data collected by the sensors.

It comes to $C = 7.86\ \text{Ah}$ or about $8\ \text{Ah}$. In view of the results obtained, the choice of a $12\ \text{V}\ 8\ \text{Ah}$ battery is obvious.

The battery powers the ESP 32 module, motors and water pump, while the mini solar panel is used to charge the battery.

In short, objective criteria such as performance, popularity, sizing and availability formed the basis for the careful selection of the various tools and equipment.

3. Results and Discussion

This section presents the various results obtained for the robot's construction, and an assessment of its cost.

3.1. Modeling the Robot Body and Roller Brush Support

The various models were created using Fusion 360 software. Figure 1 gives an overview of the robot body model created in Fusion 360.

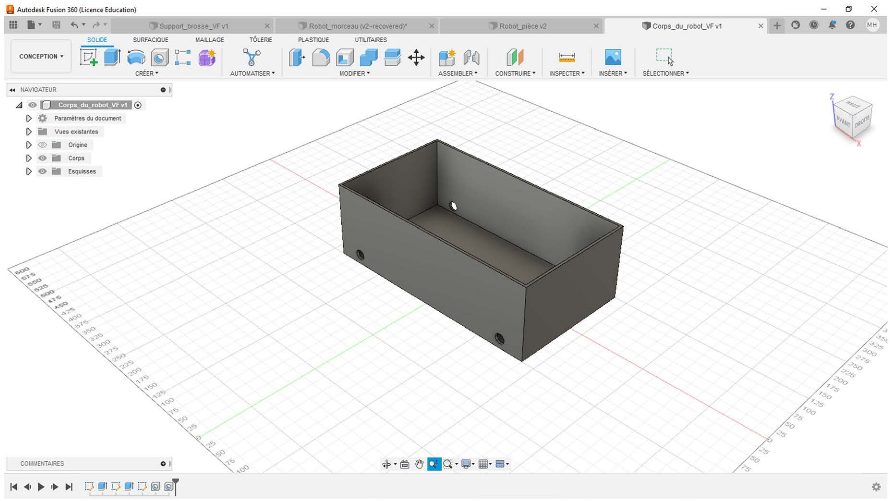

Figure 1. Overview of robot body modeling.

The roller brush holder is large enough to be printed in one go by the printer used. It was therefore broken down into three parts to be assembled after 3D printing. Figure 2 gives a back view of the roller brush support model.

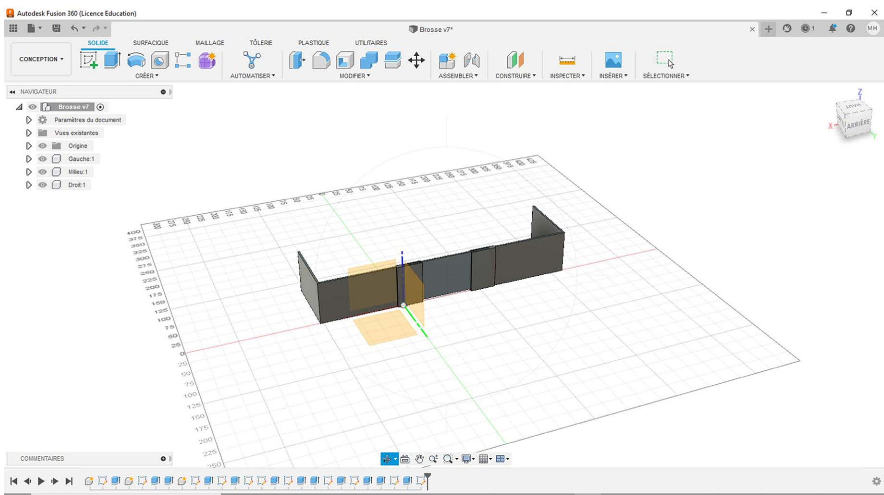

Figure 2. Back view of the brush support model.

3.2. Robot Presentation, 3D Model

Figure 3 shows the robot's two straight wheels connected by a rubber track. The photovoltaic solar module is mounted on the robot and recharges the system's battery. The roller brush is coupled to the motor designed to turn it, and the whole is carried by the roller brush support. Mini-pipes are used to supply water to the photovoltaic panels.

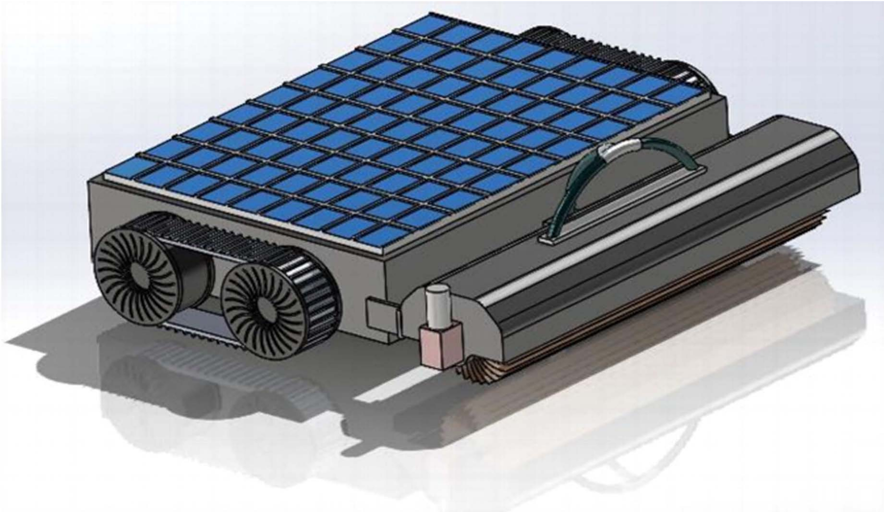

Figure 3. Robot overview.

Figure 4 is a top view of the 3D model of the robot, showing the four (04) wheels connected in pairs by a rubber track, the photovoltaic module on the robot, the brush holder and the hoses.

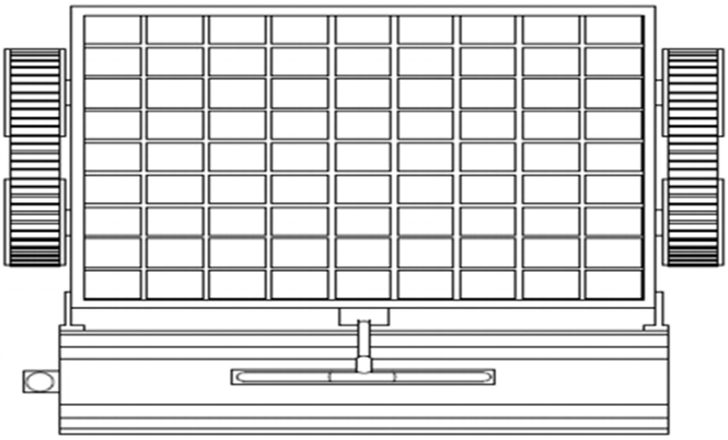

Figure 4. Robot overview, top view.

Figure 5 is a front view of the 3D robot model. It shows the robot's two front wheels, the roller brush in its holder and the motor in front of the spinner and hoses.

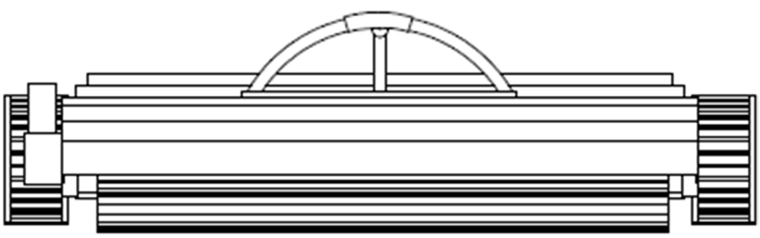

Figure 5. Overview of the robot, front view.

Figure 6 shows the right-hand side of the robot, with the two left-hand wheels connected by a rubber track. It also shows the roller brush in its holder and the hoses.

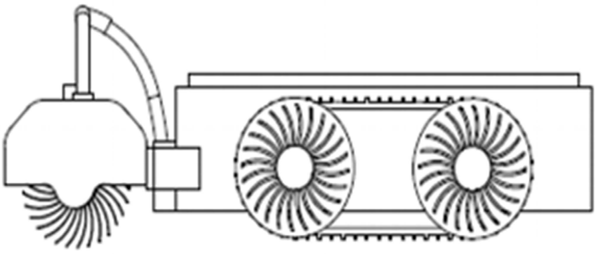

Figure 6. Robot overview, right view.

3.3. Block Diagram and System Operation

The wiring diagram of the system made with FRITZING software is shown in Figure 7.

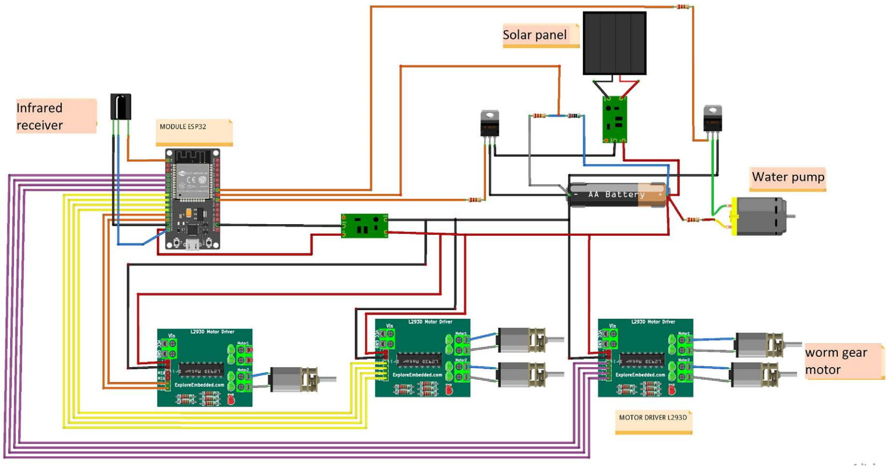

Figure 7. Electrical diagram of robotic system.

The robot is set in motion by the rotation of its four (04) wheels, each coupled to a 12 V worm gear motor. The front of the robot consists of a roller brush contained in the front support. This brush is also rotated by a motor of the same type. A water pump sends the water in front of the robot just before it passes. As the robot moves along, the rotating roller brush cleans the solar panel of dust and other impurities. Cleaning is therefore a combination of these three actions: the rotation of the wheels moving the robot, the supply of water by the pump and the rotation of the roller brush, which gently brushes the panel surface without scratching it. The robot's movements (direction of travel, steering), pump activation and brush rotation are controlled by a remote control with infrared receiver. The robot is equipped with a battery-panel assembly for power supply and a microcontroller for smart control. As the robot moves over the panels, there's no risk of scratching them, as the robot's wheels are fitted with rubber tracks that help them adhere to the walls of the photovoltaic modules.

3.4. Robot Features

Table 2 provides information on the characteristics of the photovoltaic module cleaning robot.

Table 2. Robot features.

Features	Values
Dimensions (without brush support)	40 × 25 × 15 cm
Dimensions of roller brush holder	40 × 10 × 7 cm
Robot weight	5 kg

3.5. Cost Estimate

The evaluation of the system cost takes into account the cost of each electronic component used, the cost of producing the robot body (welding and 3D printing) and labor. Table 3 below shows the costs of the components, equipment and various realizations involved in obtaining this system.

Table 3. Estimated cost of robot production.

Robot composants	Quantity	Unit price (in FCFA)	Total price (in FCFA)
Model ESP32	1	6000	6000
Gear motors	5	8000	40,000
Motor driver	3	2400	7200
Robot wheels	4	9800	39,200
Rubber tracks	2	8500	47,000
Electronic relay	1	1650	1650
Water pump	1	6500	6500
Hose	1	5000	5000
Roller brush	1	10,000	10,000
Remote control	1	810	810
Infrared receiver	2	350	700
Battery	1	5000	5000
Solar panel	1	5000	5000
Buck converter	1	1650	1650
Ohmic resistors	10	25	250
Robot body	1	35,000	35,000
3D printing	1	20,000	20,000
Workforce	1	70,000	70,000
Unforeseen	1	20,096	20,096
Total			291,056

Completion costs are estimated on the basis of the cost of components, materials and labor. The prices mentioned in Table 3 are based on local market rates for certain components purchased locally, while others that are not available in Benin have been imported, and their prices may be subject to fluctuations depending on the supplier or subject to VAT. Table 3 shows that the total estimated cost of the robot is 291,056 FCFA, broken down as follows: 200,960 FCFA for the total cost of the equipment purchased and the expenses incurred in building the robot; 70,000 FCFA for labor, taking into account 25 hours of assembly time, valued at 2000 FCFA per hour, and the remainder for the project idea and the time devoted to its development; and finally 20,096 FCFA for possible contingencies, *i.e.* 10% of the expenses. This first robot prototype could be sold for 300,000 FCFA.

3.6. Presentation of the Robot

Figure 8 shows the right-hand view of the final robot with the resources mobilized, and Figure 9 shows its perspective view.

Figure 8. Photograph of the robot.

Figure 9. Perspective view of the robot.

It should be noted that the watering system is for the moment dissociated from the robot, but controlled by the latter during cleaning. This robot is useful for any installation, whether the solar field is on a roof, on the ground or in a valley. The panels need to be cleaned when they're dirty, and a quick glance is all it takes. If the field is out of sight, it's a good idea to set a cleaning frequency according to the location of the installation (taking into account the degree of pollution in the area). Unlike the solar panel cleaning robots already on the market, our robot incorporates the feature of recharging the battery directly from a built-in photovoltaic module.

Tests have also shown that the robot shows promise in its ability to clean photovoltaic panels. However, improvements are needed to optimize its response time and incorporate the sprinkler system directly into the robot for fast, efficient cleaning. The proposed robot, like most existing solutions, is semi-automatic, as it requires the presence of a human to control the robot. Consideration could be given to making it automatic, without however taking away its semi-automatic operation.

As far as the environment is concerned, our robot poses no threat, since the equipment used to build it is recyclable and does not release CO_2 into the atmosphere during use.

4. Conclusions

The need to clean solar array is well established, as it's the ideal way to get the best performance from your photovoltaic panels. Several cleaning methods have been used for years, but the use of robots is now one of the most popular, effective and safe ways of cleaning photovoltaic solar modules. Careful selection of components, equipment and materials has resulted in an AGV (Automated Guided Vehicle) robot with four wheels linked in pairs by a rubber track. The robot is operated by an infrared remote control; water and a roller brush are used for cleaning.

The result is an autonomous robot that can be used to clean photovoltaic solar fields, whether on a roof, on the ground or in a valley. It presents no risk of damaging or scratching the panels during cleaning. It's also easy to recycle. Our robot is less expensive than existing ones, and more advantageous for any local user.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

References

[1] Institut Montaigne (2019) Solar Energy in Africa: A Radiant Future?
https://www.institutmontaigne.org/ressources/pdfs/publications/energie-solaire-en-

afrique-un-avenir-rayonnant-note.pdf

[2] Asoh, D. and Awangum, N. (2022) Low-Cost Automated PV Panel Dust Cleaning System for Rural Communities. *Smart Grid and Renewable Energy*, **13**, 173-199.

[3] Diallo, M.S. (2010) Study of the Influence of Inclination and Dust Deposits on the Performance of PV Modules in Kamboinsé (2iE site). http://documentation.2ie-edu.org/cdi2ie/opac_css/doc_num.php?explnum_id=260

[4] Rouahi, M. and Zoubir, A. (2018) Impact of Dust on the Electrical Performance Characteristics of PV Modules. Master's Thesis, Université Ahmed Draïa ADRAR. https://dspace.univ-adrar.edu.dz/jspui/handle/123456789/1394

[5] (2022) Why and How to Clean Solar Panels. https://fr.everexceed.com/blog/why-when-and-how-to-clean-solar-panels_b157

[6] Gnonlonfoun, A.F.M. and Akowanou, D.C. (2020) Design of an Intelligent System for Measuring Consumption and Identifying Electrical Equipment. Design Engineer Thesis at ENSGEP/UNSTIM Benin, 80.

[7] Nkinyam, C.M., Ujah, C.O., Nnakwo, K.C., Ezeudu, O., Kallon, D.V.V. and Ezema, I.I.C. (2024) Design and Implementation of a Waterless Solar Panel Cleaning System. *Unconventional Resources*, **5**, Article ID: 100131.

[8] Djemenda, N.F. (2015) Implementation and Execution of a Protocol for Studying and Monitoring the Cleaning of Photovoltaic Modules in Very Dusty Areas: The Case of the Sudano-Sahelian Region. http://documentation.2ie-edu.org/cdi2ie/opac_css/doc_num.php?explnum_id=2065

[9] Kouadria M. (2024) Microprocessors and Microcontrollers. https://fsa.univ-tiaret.dz/doc/COURS/COURS_Microprocesseurs_Microcontroleurs.pdf

[10] JDN (2020) Bluetooth: Definition and Operation. https://www.journaldunet.fr/webtech/dictionnaire-de-l-iot/1203379-bluetooth-definition-et-fonctionnement/

Nomenclature

A	Exchange surface, m^2
B	System energy requirements, Wh
C	Battery capacity, Ah
Co	Motor torque, N·m
D	Battery discharge rate
d	Wheel diameter, m
F	Strength, N
Ir	Minimum irradiation per day, $kWh \cdot m^{-2}$
m	Robot mass, kg
N	Number of motors
n	Number of days of autonomy
p	Motor power, W
Po	robot weight, N
R	Reduction ratio between wheels and motors
U	Battery voltage, V
v	Maximum robot speed, $m \cdot s^{-1}$

Greek letters

α	Angle of the slope on which the robot can climb
ω	Motor speed, $tr \cdot mn^{-1}$

Subscripts

p	Peak
m	Motor