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A REVIEW ON AUTOMATED PV SOLAR PANEL CLEANING SYSTEM WITH OBSTACLE DETECTION

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ABSTRACT

Solar photovoltaic (PV) panels are becoming an important source of clean and renewable energy.However, the performance of solar panels decreases when dust and dirt accu-mulate on their surface.Dust blocks sunlight from reaching the panel properly, which reducestheoverallpowergenerationefficiency.Regularcleaningisthereforenecessary to maintain maximum energy output.

In many real-life situations, cleaning solar panels manually is difficult, time-consuming, and sometimes risky, especially in large solar installations or rooftop systems.To over-come these problems, an automatic solar panel cleaning system is developed to reduce human effort and improve cleaning efficiency.

This project focuses on the design and implementation of an automated PV solarcleanerusingamotor-drivencleaningmechanismalongwithawatersprayingsystem. The system is controlled using a microcontroller that manages the movement of thecleaner, operation of the rotating brush, and water pump control. An obstacle detection featureisalsoincludedtoensuresafemovementofthecleanerandtoavoiddamageat the panel edges. The proposed system combines both dry and wet cleaning methods for better removalof dust and dirt while reducing unnecessary water consumption.The rotating brush helps remove dry particles, while the water spray assists in cleaning stubborn dirt from the panel surface.

Thedevelopedprototypedemonstratesthatautomationcansignificantlyimproveso-larpanelmaintenanceandhelpmaintainhigherenergyefficiency.Thesystemisdesigned to be cost-effective, reliable, and easy to operate, making it suitable for residential and small-

scale industrial solar applications.

KEYWORDS: Solar panel cleaning system, photovoltaic (PV), automation, dust removal, microcontroller,obstacledetection,rotatingbrush,waterpump,renewableenergy.

INTRODUCTION

A photovoltaic (PV) solar panel cleaning system is an automated setup developed to maintain the efficiency and performance of solar panels by removing dust, dirt, and other unwanted particles from their surface. When dust accumulates on solar panels, a con-diction commonly called soiling, it blocks sunlight from reaching the photo voltaic cells and reduces the overall power generation capacity of the system. In large-scale solar in-stallations and rooftop systems located at difficult or elevated positions, manual cleaning becomes labor-intensive, costly, and sometimes risky.For this reason, automated cleaning technologies are being adopted to improve panel efficiency while reducing human effortand maintenance requirements. [2,3,5] In real-world applications, the effectiveness of a so-lar panel cleaning system mainly depends on two important factors:proper dust removal and smooth operation of the cleaning mechanism.Most automated systems consist of mechanical and electronic components such as DC motors, rotating brushes, rollers, and watersprayingunits.Therotatingbrushremovesthedustdepositedonthepanelsur-face, while the water pump assists in cleaning stubborn dirt and improves overall cleaning quality. [3,5,12] Despite these advantages, certain challenges still exist, including incom-plete cleaning, unnecessary water consumption, and instability in the movement of the system.Therefore, proper design and control techniques are required to achieve reliable andefficientoperation.Differentcleaningtechniquessuchasdrycleaning,wetclean-ing, and hybrid cleaning methods have been proposed in previous studies. Among these methods, the combination of brush cleaning with water spraying is considered one of the most effective approaches because it provides better dust removal and improves cleaning efficiency. [4,6] To make the system fully automatic and safe, embedded controllers and microcontroller-based circuits are commonly used for controlling motor movement, brush rotation, and water flow.In addition, obstacle and edge detection sensors are often in-cluded to protect the mechanism from damage and ensure safe movement across the solar panel surface. [1]

Thispaperfocusesonthedesignanddevelopmentofanautomatedsolarpanelclean-ingsystemthatintegratesmechanicalcleaning,waterspraying,andembeddedcontrol. The proposed system emphasizes low-cost implementation, efficient cleaning performance, andreliableoperation,makingitsuitableforresidentialandsmall-scalesolarinstalla-tions.

WORKING PRINCIPLE OF AUTOMATED PV SO-LARPANELCLEANINGSYSTEM

The working of the automated solar panel cleaning system can be compared to a moving cleaning platform that continuously removes dust from the panel surface. As the system movesforwardoverthesolarpanel,thecleaningmechanismoperatessimultaneouslyto ensure effective dust removal. When the system encounters dust or dirt, a rotatingbrush removes loose particles, while the water spraying system helps to clean dirt.This combinedactionimprovesthecleaningefficiencyandrestoresthepanelperformance.

Theentireprocessiscontrolledusingamicrocontroller,wheresensorsandactuators work together in real time [1].

Closed Loop Operation

Inthecleaningloop:

- ThesystemmovesacrossthesolarpanelusingDCmotors.
- Thecontrolleractivatesthewaterpumpandbrushmechanism.
- Dustanddirtareremovedusingbrushrotationandwaterspray.
- Obstaclesensordetectsedgesorbarriers.
- Thesystemstopsorchangesdirectiontopreventdamage.

Practical Requirements for Cleaning

Forpropercleaning,thesystemmustsatisfy:

- Smoothanduniformmovementacrossthepanel.
- Effectivedustremovalusingbrushandwater.
- Controlledwaterusagetoavoidwastage.
- Reliablesensoroperationforsafetyandedgedetection.

SYSTEM MODELING OF AUTOMATED PVSO-LARPANELCLEANINGSYSTEM

Systemmodelingisimportantforanalyzingthemovementandcleaningperformanceofthesolarpanelcleaningrobot.Inthisproject,thecleaningsystemisrepresentedas a mechanical platform that performs both linear movement and rotational cleaning operations.The robot moves across the surface of the solar panel while the rotating brush removes dust and dirt from the panel surface.Key parameters considered in the model includewheelradius,speedofthedrivemotor,rotationalspeedofthecleaningbrush, andtherateofwaterflowusedduringcleaning.[4,13]

Motion and Cleaning Model

The motion and cleaning operation of the PV Solar Cleaner are based on the coordinated movement of the cleaning platform and the rotating brush mechanism.The system moves linearly across the surface of the solar panel while the rotating brush removes accumulated dust,dirt,andsmalldebrisfromthepanelsurface.

The linear motion is achieved using DC motors connected to wheels or a rail mechanism,allowingthecleanertotravelsmoothlyoverthepanel.Simultaneously,therotating brushcontinuouslysweepsthesurfacetoensureeffectivecleaningwithoutdamagingthe solar panel glass.

The cleaning efficiency depends on several factors such as:

- Speedofmovementofthecleaningsystem
- Rotationalspeedofthebrush
- Brushmaterialandcontactpressure
- Amountofdustaccumulatedonthepanel
- Powersuppliedtothemotors

A controlled movement mechanism ensures uniform cleaning over the entire panel surface.Ifthesystemmovestoofast,somedustparticlesmayremainonthepanel,while very slow movement may increase energy consumption and cleaning time.Therefore, propersynchronizationbetweenbrushrotationandplatformmovementisimportantfor efficient operation.

The motion control system can also include sensors and programmed timing control to automatically start, stop, and reverse the cleaner when it reaches the edges of the solar panel.This improves automation, reduces manual effort, and enhances overall cleaning performance.

Thecombinedmotionandcleaningmechanismhelpsmaintainmaximumsolarpanel efficiency by reducing dust accumulation and improving sunlight absorption.

Importance of Modeling in Cleaning System

This modeling approach is important because it describes the relationship between system movement and cleaning performance.It helps in selecting appropriate motor speed, brush rotation,and water flow rate for effective cleaning.Although detailed nonlinear modelscan be developed, most practical implementations use simplified models for easier control andsystemdesign.Propermodelingensuressmoothoperation,efficientdustremoval, and reduced energy consumption.

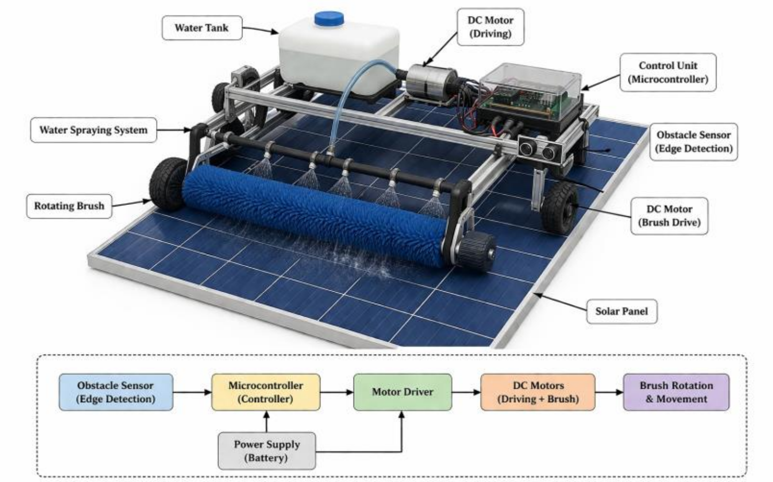

Figure: Conceptual model of automated PV solar panel cleaning system.

Figure1: Conceptual model of automated solar panel cleaning system.

SENSORSYSTEMANDOBSTACLEDETECTION

Sensor integration is an important part of the automated solar panel cleaning system to ensuresafeandefficientoperation.Unlikebalancingrobots,thissystemdoesnotrequire tiltestimation,butitreliesonsensorstodetectobstaclesandpaneledges.Inthisproject, an obstacle detection sensor (IR or ultrasonic) is used to monitor the surroundings and prevent the system from falling off the panel or colliding with objects [1].

Obstacle Detection Sensor

The obstacle sensor detects the presence of an object or panel edge based on reflected signals.The sensor output can be represented as $S(k)$, where k indicates the current samplinginstant.Theoutputistypicallybinary:

- $S(k) = 1$→Obstacledetected
- $S(k)=0$→Noobstacle

The decision logic can be expressed as:

$$D(k) = \begin{cases} 1, & \text{ifobstacleisdetected} \\ 0, & \text{otherwise} \end{cases} \qquad (1)$$

When an obstacle is detected, the controller immediately stops or changes the direction of the system to ensure safety.

Water Flow Control System

The cleaning efficiency depends on proper control of water flow.The water pump is activated through a relay module based on control signals from the microcontroller.The water flow can be represented as:

Need of Sensor Integration

Sensor integration is necessary to ensure reliable system performance.The obstacle detec-tion system prevents damage to the solar panel and cleaning robot, while controlled water flow ensures efficient cleaning without wastage.Proper coordination between sensors and actuatorsimprovessystemreliabilityandoperationalsafety.

CONTROL STRATEGY FOR AUTOMATED CLEAN-ING SYSTEM

In the proposed solar panel cleaning system, complex sensor fusion techniques such as complementaryfilteringarenotrequired.Instead,asimpleandefficientcontrolstrategy is implemented using a microcontroller to coordinate the movement, cleaning action, and safety mechanisms.The system integrates inputs from obstacle sensors and generates controlsignalsformotorsandthewaterpump[1].

SystemCoordination

Themicrocontrollermanagesmultipleoperationssimultaneously:

- ControlsDCmotorsforforwardandreversemotion.
- Activatesrotatingbrushfordustremoval.
- Operateswaterpumpthroughrelaymodule.
- Processesobstaclesensorinputforsafety.

Advantages

- Simpleandefficientcontrolimplementation.
- Lowcomputationalrequirement.
- Real-timeresponsetosensorinputs.
- Reliableandcost-effectivesystemoperation.

ADVANCEDCONTROLANDSYSTEMOPTIMIZA-TION

In the proposed solar panel cleaning system,complex estimation techniques such asKalman filtering are not required since the system does not involve dynamic balancing ortiltestimation.However,advancedcontrolandoptimizationtechniquescanbeapplied toimprovesystemefficiency,reliability,andresourceutilization.Thesetechniquesfo-cus on optimizing cleaning performance, reducing water consumption, and ensuring safe operation [1].

Adaptive Cleaning Strategy

An adaptive cleaning approach can be implemented where system parameters are adjusted based on surface conditions.For example:

- Increasebrushspeedforheavydustaccumulation.
- Increasewaterflowforstubborndirt.
- Reducespeedforbettercleaningcoverage.

Two-StageCleaningProcess

Inpracticalimplementations,atwo-stagecleaningprocesscanimproveperformance:

- **Stage1:**Drycleaningusingrotatingbrushtoremoveloosedust.
- **Stage2:**Wetcleaningusingwatersprayfordeepcleaning.

Thisapproachimprovescleaningefficiencywhileminimizingwaterusage.

SystemOptimizationBenefits

Theoptimizedcontrolstrategyprovides:

- Improvedcleaningefficiency.
- Reducedwaterconsumption.
- Betterenergy utilization.
- Enhancedsystemreliabilityandsafety.

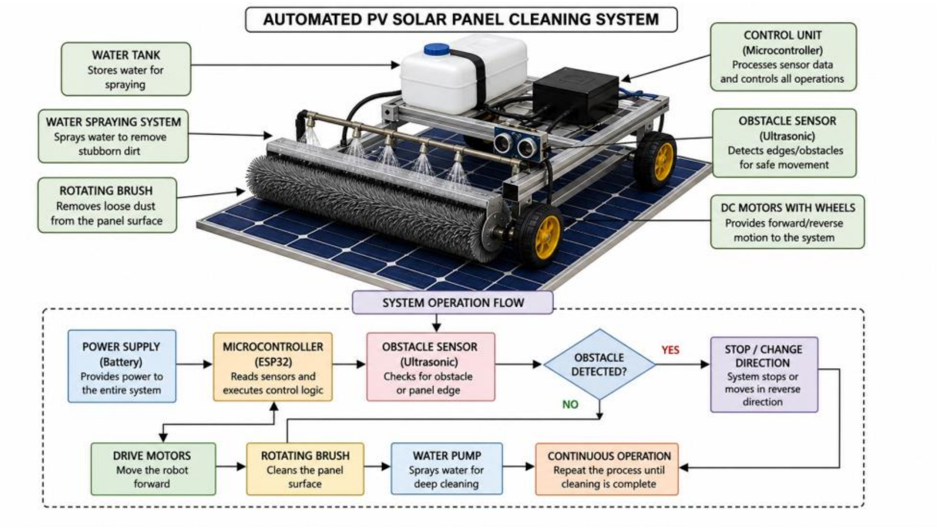

Figure2: Two-Stage Sensor Fusion and Control Flow.

Comparison of Cleaning Methods and Control Approaches

In solar panel cleaning systems,simple microcontroller-based control is commonly useddue to low cost and easy implementation, while advanced IoT or adaptive methods offer betterperformancebutaddcomplexity.Drycleaningwithabrushisfastandwater-free but less effective for tough dirt, whereas wet cleaning improves efficiency but needs water management. Therefore, a hybrid approach combining both methods is preferred. Overall, simple rule-based control is ideal for low-cost systems because it provides fast, reliable operationwith minimal complexity.

Table1:Comparison of Cleaning Method sin Automated PV Solar Panel Systems.

Aspect	**Dry Cleaning (Brush Only)**	**WetCleaning(Brush+Wa-ter)**
Cleaning Effi-ciency	Moderate	High
WaterUsage	Notrequired	Required
DustRemoval	Removes loose dust only	Removes dust+ stubborn dirt
Maintenance	Low	Moderate
Cost	Low	Slightlyhigher
Suitability	Small-scale/low dust areas	Allenviron-ments / heavy dust
Best Fit for Project	Basic cleaning systems	Hybridcleaning (recommended)

CONTROL STRATEGIES FOR AUTOMATEDSO-LARPANELCLEANINGSYSTEM

After detecting system conditions such as obstacle presence and cleaning requirements,the controller generates appropriate control signals for movement, brush operation, and water flow.Various control approaches are used in automated solar panel cleaning systems dependingonsystemcomplexityandapplicationrequirements.

Microcontroller-BasedControl

Microcontroller-based control is widely used due to its simplicity, low cost, and ease of implementation.In this system, the ESP32 processes sensor inputs and generates control signals for DC motors, water pump, and brush mechanism.This approach ensures reliable real-timeoperationforcleaningapplications[1,6,7,9].

Rule-BasedControl

A rule-based control strategy is implemented in the proposed system.The controller follows predefined conditions such as:

- Moveforwardwhennoobstacleisdetected.
- Stoporreversewhenanobstacleoredgeisdetected.
- Activatebrushandwaterpumpduringcleaning.

This method is simple, efficient, and suitable for embedded systems with limited computational requirements.

Advanced Control Approaches

In advanced systems, adaptive or IoT-based control strategies can be used to optimize cleaning performance. These methods allow dynamic adjustment of cleaning parameters such as speed and water flow based on environmental conditions [4,6,7,13].However,they increase system complexity and cost.

Overall, microcontroller-based rule control is preferred for low-cost solar panel cleaning systemsduetoitsreliabilityandeaseofimplementation.

ESP32BASEDIMPLEMENTATION

Real-time operation of the automated solar panel cleaning system requires efficient processingandcontrolofsensorsandactuators.TheESP32microcontrollerisusedasthe main control unit due to its high processing capability, low power consumption, and integrated wireless communication features.

WhyESP32?

ESP32provides:

- Dual-coreprocessorforreal-timeembeddedcontrol.
- Built-inWi-FiandBluetoothforfutureIoTapplications.
- MultipleGPIOpinsforinterfacingsensorsandactuators.
- PWMgenerationcapabilityformotorspeedcontrol.

ThesefeaturesmakeESP32suitableforautomatedsolarpanelcleaningsystems[1].

ProposedControlPipeline

Thesystemoperatesbasedonthefollowingcontrolflow:

- Readingobstaclesensorinputs.
- ProcessingcontrollogicinESP32.
- DrivingDCmotorsforforwardandreversemotion.
- Activatingrotatingbrushforcleaning.
- Controllingwaterpumpusingrelaymodule.

TheESP32processesalloperationsinrealtime,ensuringsmoothandefficientclean-ing.

Relay-Based Pump Control

ThewaterpumpiscontrolledusingarelaymoduleconnectedtoESP32.Therelayacts as a switching device to turn the pump ON or OFF based on cleaning requirements,ensuring controlled water usage and power efficiency.

System Advantages

ComparedtoFPGA-basedsystems,ESP32implementationprovides:

- Lowcostandcompactdesign.
- Simplerimplementationanddebugging.
- Sufficientprocessingspeedforreal-timecontrol.
- EasyscalabilityforIoT-basedmonitoring.

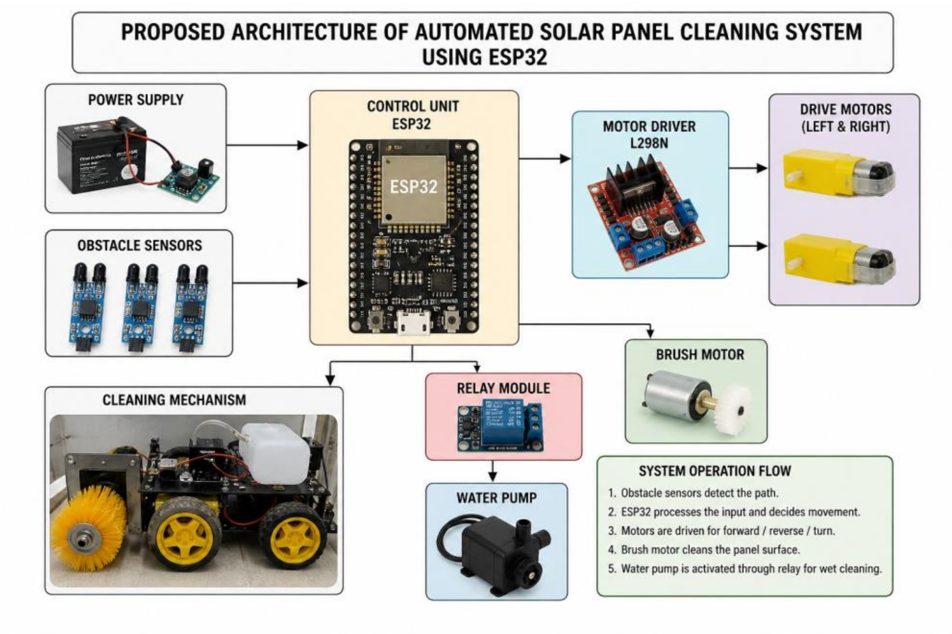

Figure 3: Proposed ESP32-Based Architecture of Automated PV Solar Panel Cleaning System.

Sensor-BasedControlandSystemOperation

Fig. 3 shows the ESP32-based control architecture of the automated solar panel cleaning system.The system uses an obstacle detection sensor (IR/ultrasonic) to monitor the surroundings and ensure safe movement over the panel surface.

The sensor provides input signals indicating the presence or absence of an obstacle. Basedonthis input,theESP32 processesthedataandgeneratesappropriatecontrol signals for system operation.

The Generated control signals are then applied to:

- DCmotorsformovement,
- Rotatingbrushfordustremoval,
- Waterpumpforwetcleaning.

PWM signals generated by ESP32 control the motor speed, ensuring smooth andefficient operation of the cleaning system.

NAVIGATIONANDADVANCEDCAPABILITIES

Theautomatedsolarpanelcleaningsystemcanbeextendedwithadditionalnavigation andsmartfeaturesforimprovedperformanceandusability.Inthecurrentimplementa-tion,basicobstacledetectionisusedtoensuresafemovementacrossthepanelsurface. Advancednavigationcanbeachievedusingmultiplesensorsandcontrolalgorithms to enable autonomous movement across large solar panel arrays.Obstacle detection sensorshelpinidentifyingpaneledgesandpreventingsystemdamage.Futuresystems canincorporatepathplanningtechniquesforcompletepanelcoverage.

Integration of IoT technology can further enhance system capabilities.The ESP32 microcontroller supports wireless communication, allowing remote monitoring and control of the cleaning system.Parameters such as cleaning status, battery level, and system operation can be monitored in real time [1].
Additionally, smart scheduling can be implemented to automate cleaning at regular intervals, improving overall efficiency of the solar panels.These advanced capabilities make the system suitable for large-scale solar installations and industrial applications.

HARDWAREREQUIREMENTSANDSYSTEMCOM-PONENTS

The performance of the automated solar panel cleaning system depends on the proper selectionofmechanicalandelectroniccomponents.Theproposedsystemisdesigned using an ESP32 microcontroller, DC motors, a rotating brush mechanism, and a water spraying unit for effective cleaning.

MechanicalComponents

The mechanical structure should be stable and lightweight to ensure smooth movement acrossthesolarpanelsurface.Thekeymechanicalcomponentsinclude:

- FourDCgearedmotorswithwheelsformovement.
- Rotatingcylindricalbrushfordustremoval.
- Chassis/frametosupportallcomponents.
- Watertankandpipesystemforwetcleaning.

A well-balanced mechanical design ensures uniform motion and effective cleaning performance.

Electronic Components

Themainelectroniccomponentsusedinthesystemare:

- **ESP32Microcontroller:**Actsasthemaincontrolunitforprocessingsensor inputs and controlling system operation.
- **Motor Driver (L298N):**UsedtocontrolspeedanddirectionofDCmotorsusing PWM signals.

- **ObstacleSensor(IR/Ultrasonic):**Detectsedgesorobstaclestopreventsystem damage.
- **RelayModule:**Controlsthewaterpumpoperation.
- **WaterPump:**Sprayswaterforeffectivecleaning.
- **LCDDisplay(16x2):**Displayssystemstatussuchasobstacledetection.

Power and Safety Considerations

Inpracticalimplementation,properpowerdistributionisrequired:

- Motorsandpumparepowered usinga12Vbattery.
- ESP32andsensorsarepoweredusingregulated5V/3.3Vsupply.

This separation prevents voltage fluctuations caused by motors, ensuring stable operationof the controller and sensors.

LIMITATIONSANDPRACTICALCHALLENGES

Althoughtheautomatedsolarpanelcleaningsystemprovidesaneffectivesolutionfor dustremoval,severalpracticalchallengesareobservedduringimplementation.

Mechanical Design Issues

Uneven weight distribution of components such as the water tank and motors can affect smoothmovementacrossthepanel.Improperalignmentoftherotatingbrushmaylead to inefficient cleaning.

Water Management

Excessive water usage can lead to wastage, while insufficient water may not remove stubborn dirt effectively.Proper control of water flow is required to maintain cleaning efficiency.

Surface Navigation Challenges

The system must operate on inclined and smooth panel surfaces.Slippage of wheels or improper tractioncan affect movementand cleaning coverage.

Sensor Limitations

Obstacle detection sensors may sometimes give incorrect readings due to sunlight inter-ferenceorreflectivesurfaces.Thiscanaffectedgedetectionandsystemsafety.

Power Consumption

DC motors and water pump consume significant power,which reduces battery backuptime.Efficientpowermanagementisnecessaryforlongeroperation.

Environmental Factors

External conditions such as dust type, humidity, and weather can influence cleaning performance.Stickyoroilydirtmayrequiremoreadvancedcleaningtechniques.

FUTURE SCOPE

The proposed automated solar panel cleaning system can be further improved by inte-gratingadvancedfeaturestoenhanceperformance,efficiency,andusability.

Automatic Scheduling System

Thesystemcanbeupgradedtoperformcleaningoperationsautomaticallyatpredefined time intervals.This ensures regular maintenance of solar panels without human inter-vention.

IoT-BasedMonitoring

Since ESP32 supports Wi-Fi, the system can be integrated with IoT platforms for remote monitoring and control.Parameters such as cleaning status, battery level, and system performance can be monitored in real time [1].

Solar-PoweredOperation

The system can be made self-sustainable by using a small solar panel to charge the battery. Thisreducesdependencyonexternalpowersourcesandimprovesenergyefficiency.

Advanced Navigation System

Future versions can include advanced navigation techniques such as path planning and multi-sensorintegrationtocoverlargesolarpanelarraysefficiently.

Waterless Cleaning Technology

Toreducewaterusage,drycleaningtechniquessuchaselectrostaticdustremovalor air-based cleaning systems can be implemented.

AI-BasedDustDetection

Artificialintelligencetechniquescanbeusedtodetectdustlevelsandactivatecleaning onlywhenrequired.Thisimprovesefficiencyandreducesunnecessaryoperation.

ImprovedMechanicalDesign

Thesystemcanbeoptimizedwithlightweightmaterialsandbettertractionmechanisms toimprovestabilityandperformanceoninclinedsurfaces.

RESEARCH GAP AND PROPOSED OUT COME

Fromthereviewedliterature,itisobservedthatmanyexistingsolarpanelcleaningsys-temsareeithermanualorpartiallyautomated,whichleadstoinconsistentcleaningand increased maintenance effort.Some automated systems are complex and expensive, mak-ingthemunsuitableforsmall-scaleorresidentialapplications.Additionally,manysys-temsfocusonlyoneitherdryorwetcleaning,whichreducesoverallcleaningefficiency. Itisalsoobservedthatlimitedattentionhasbeengiventolow-cost,simple,andfully automated solutions that integrate both effective cleaning mechanisms and safety features suchasobstacledetection.Furthermore,issuessuchaswaterwastage,powerconsump-tion, and system reliability are not adequately addressed in many existing designs.

Hence,basedontheseobservations,theproposedprojectfocuseson:

1. Designingalow-costautomatedsolarpanelcleaningsystemusingESP32micro-controller,
2. Implementing a hybrid cleaning mechanismusing rotatingbrush andwater spray,
3. Integratingobstacledetectionforsafeandreliableoperation,
4. Developingacompactandefficientsystemsuitableforresidentialandsmall-scale applications withimprovedresponse.

CONCLUSION

This paper presented the design and implementation of an automated PV solar panel cleaning system using an ESP32-based control approach.The system integrates a mobile cleaning mechanism, rotating brush, water spraying unit, and obstacle detection to ensure effective and safe operation.The proposed system successfully reduces dust accumulation on solar panels, thereby improving energy efficiency and reducing manual maintenance effort.

The use of a microcontroller-based control strategy provides a simple, low-cost, and reliable solution suitable for residential and small-scale applications.Experimental obser-vations indicate that the system operates efficiently with smooth movement and effective cleaning performance.

Overall, the developed system offers a practical and scalable solution for solar panel maintenance and can be further enhanced with advanced features such as IoT integration and automatic scheduling.

DECLARATIONOFINTEREST

The authors declare that there is no conflict of interest regarding the publication of this research work.

ETHICSAPPROVAL

This research work does not involve human participants or animal experiments.Hence, ethics approval is not applicable.

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