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Solar Based Advanced Air Purifier

Kushal Kumar S[1], Monish Raj D. V.[2], Pavan Kumar M. P.[3], Prabhakar Reddy B. M[4]., Professor Suman A. H[5]

[1,2,3,4]Department of Electrical and Electronics Engineering Bangalore Institute of Technology, Bangalore,India
[5]Associate Professor, Dept. of Electrical and Electronics Engineering, Bangalore Institute of Technology, Bangalore-04, India

Abstract- The Solar-Powered Smart Air Purification Sys- tem represents a revolutionary approach to addressing out- door air pollution through autonomous, renewable energy- driven technology. This innovative system combines micro- controller architecture with solar power generation to create a self-sustaining mobile air purification unit capable of de- tecting, analyzing, and treating localized air quality issues in real-time. The system integrates advanced sensor technologies including Light Dependent Resistor (LDR) sensors for partic- ulate matter detection and MQ series gas sensors for compre- hensive air quality monitoring, enabling precise identification of pollution hotspots. Upon detection of suboptimal air con- ditions, the system autonomously activates its HEPA filtration mechanism through relay-controlled switching, providing im- mediate and targeted air purification. The solar-powered de- sign ensures continuous operation during daylight hours while maintaining energy efficiency through intelligent power man- agement. This eco-friendly solution addresses the growing need for localized air quality management in outdoor environ- ments, offering a scalable and sustainable approach to envi- ronmental protection.

Keywords: Solar power, air purifier, HEPA, ESP32, AQI, mobile robot.

I. INTRODUCTION

Air pollution has emerged as one of the most pressing en- vironmental challenges of the 21st century, significantly im- pacting public health, ecosystem stability, and quality of life across urban and industrial areas worldwide. Traditional air purification systems are typically stationary, energy-intensive, and limited in their coverage area, making them inadequate for addressing dynamic outdoor air quality issues. The increasing urbanization and industrial activities have created a demand for innovative solutions that can provide mobile, efficient, and environmentally conscious air purification capabilities. The Solar-Powered Smart Air Purification System addresses these limitations by introducing an autonomous, renewable energy-powered robotic platform designed specifically for outdoor air quality management. This system leverages the advancement in microcontroller technology, sensor integration, and renew- able energy systems to create a comprehensive solution that can independently monitor, analyze, and improve air quality in targeted areas. The integration of Arduino-based control systems with solar power technology represents a significant step forward in developing sustainable environmental protec- tion tools that can operate continuously without relying on tra- ditional power infrastructure.

The scope of the Solar-Powered Smart Air Purification Sys- tem encompasses multiple technical and environmental do- mains, positioning it as a versatile solution for various outdoor air quality challenges. The system is designed to operate effec- tively in diverse outdoor environments including urban parks, industrial zones, residential areas, construction sites, and pub- lic spaces where air quality monitoring and improvement are critical. The technical scope includes autonomous navigation capabilities enabling the robot to patrol designated areas, com- prehensive air quality sensing through multiple sensor types, real-time data processing and decision-making algorithms, and efficient power management through solar energy harvesting. The system's operational scope extends to continuous 24-hour monitoring with daylight-powered active purification, adaptive response to varying pollution levels, and scalable deployment options for both individual units and coordinated multi-robot systems. Furthermore, the scope encompasses future expand- ability through modular design principles, allowing for inte- gration of additional sensors, communication modules, and enhanced filtration technologies. The environmental scope ad- dresses particulate matter reduction, gas pollutant neutraliza- tion, and localized air quality improvement, making it suitable for both preventive environmental protection and responsive pollution mitigation strategies.

Current air purification systems in the market primarily consist of stationary indoor units, large-scale industrial air treatment facilities, and passive environmental protection mea- sures such as tree planting and emission regulations. Existing indoor air purifiers typically utilize HEPA filtration, activated carbon filters, or ionization technologies, but are limited to en- closed spaces and require continuous electrical power from the grid, making them unsuitable for outdoor applications. In- dustrial air treatment systems, while effective for large-scale operations, are extremely energy-intensive, require significant infrastructure investment, and are designed for fixed installa- tions rather than mobile or adaptive deployment. Some ex- isting outdoor air quality solutions include air quality mon- itoring stations that provide data collection and analysis but lack active purification capabilities, and large-scale urban air methane gas is present, the resistance of the sensor decreases, and this change can be measured as an output voltage, which is proportional to the concentration of methane.

The Solar-Powered Smart Air Purification System operates through a sophisticated integration of renewable energy gen- eration, intelligent sensing, autonomous navigation, and ac- tive air purification processes. During daylight hours, the so- lar panels continuously harvest solar energy and charge the onboard battery system through a regulated charging circuit, ensuring sustained operation and energy storage for periods of reduced sunlight. The Arduino microcontroller continu- ously monitors inputs from the sensor array, with LDR sen- sors providing real-time data on particulate matter concentra- tions and MQ sensors analyzing gaseous pollutant levels in the surrounding air. The system processes this environmental data through programmed algorithms that establish air qual- ity thresholds and determine when purification intervention is necessary. When air quality readings exceed predetermined pollution levels, the Arduino activates the navigation system through motor driver circuits, directing the robot to position itself optimally for maximum purification effectiveness. Upon reaching the target location, the microcontroller activates the relay system, which switches on the HEPA filtration circuit, beginning immediate air purification processes. The filtra- tion system draws contaminated air through the HEPA filter, removing particulate matter and improving local air quality while the robot maintains its position for optimal treatment duration. Throughout the operation, the system continuously monitors both air quality improvements and power consump- tion, adjusting operational parameters to maintain efficiency while maximizing environmental impact. The autonomous navigation system enables the robot to patrol designated ar- eas, creating a systematic approach to air quality management that addresses multiple locations while optimizing energy uti- lization and purification effectiveness.

In summary,the Solar-Powered Smart Air Purification Sys- tem represents a significant advancement in autonomous en- vironmental protection technology, successfully demonstrat- ing the feasibility of combining renewable energy, intelligent sensing, and active air purification in a mobile robotic plat- form. The integration of Arduino microcontroller technology with solar power generation creates a sustainable solution that operates independently while providing measurable air quality improvements in outdoor environments. The system’s ability to detect, analyze, and respond to air quality issues in real- time addresses a critical gap in current environmental protec- tion capabilities, offering a proactive approach to pollution management that complements existing regulatory and moni- toring systems. The successful implementation of HEPA filtration technology in a mobile, solar-powered configuration proves the viability of extending indoor air purification con- cepts to outdoor applications, opening new possibilities for lo- calized environmental intervention. The autonomous naviga- tion and intelligent decision-making capabilities demonstrate the potential for scalable deployment of multiple units to pro- vide comprehensive air quality management across larger ar- eas. The project's emphasis on renewable energy utilization ensures that the solution contributes positively to environmen- tal protection without adding to conventional energy consump- tion or carbon emissions. Future development opportunities include integration of advanced communication systems for coordinated multi-robot operations, expansion of sensor capa- bilities for broader pollutant detection, and enhancement of fil- tration technologies for improved purification efficiency. The Solar-Powered Smart Air Purification System establishes a foundation for next-generation environmental protection tools that combine sustainability, intelligence, and effectiveness in addressing the growing challenges of air pollution in outdoor environments.

II. BLOCK DIAGRAM AND HARDWARE

DESCRIPTION

- **Block Diagram:**

The overall block diagram of Solar Powered Advanced Air Purifier is illustrated in Fig. 1. It operates through a so- phisticated integration of multiple electronic and mechanical components working in perfect synchronization to achieve au- tonomous air quality management. The central processing unit consists of an ESP-32 microcontroller, which serves as the brain of the entire system, processing sensor inputs, making intelligent decisions, and controlling all operational aspects of the robot. The microcontroller runs a continuous loop program that monitors environmental conditions, processes data from multiple sensors, and executes appropriate responses based on predetermined algorithms and threshold values.

The power generation and management system forms the foundation of the robot's energy independence, utilizing high- efficiency monocrystalline or polycrystalline solar panels rated between 20-50 watts depending on system requirements. These solar panels are connected to a battery. The energy stor- age consists of deep-cycle lithium-ion or lead-acid batteries with sufficient capacity to maintain operations during periods of reduced sunlight or nighttime monitoring activities. A volt- age regulator circuit ensures stable power supply to all elec- tronic components, protecting sensitive circuitry from volt- age fluctuations and maintaining consistent operational perfor- mance.

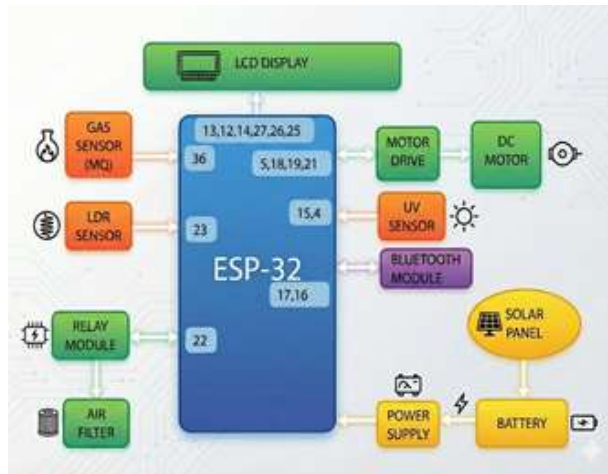

Figure 1: Block Diagram of Solar Powered Advanced Air Pu- rifier

The environmental sensing array represents the system's ability to perceive and analyze air quality conditions in real- time. Light Dependent Resistor (LDR) sensors are strategi- cally positioned to detect changes in light transmission through the air, which correlates directly with particulate matter con- centration and dust levels. These sensors operate on the prin- ciple that increased particulate matter in the air reduces light transmission, causing measurable changes in the LDR's re- sistance values. The system typically employs multiple LDR sensors at different heights and orientations to provide com- prehensive particulate matter assessment. MQ series gas sen- sors, including MQ-2, MQ-7, MQ-135, and others, are in- tegrated to detect specific gaseous pollutants such as car- bon monoxide, carbon dioxide, ammonia, benzene, alco- hol, and smoke particles. Each MQ sensor operates through a heated metal oxide semiconductor that changes resistance when exposed to target gases, providing analog voltage out- puts proportional to gas concentrations.

The locomotion system enables autonomous navigation through a combination of DC motors, motor driver circuits, and wheel assemblies designed for outdoor terrain naviga- tion. The motor driver, typically an L298N or similar H- bridge circuit, receives digital signals from the ESP 32 and converts them into appropriate voltage and current levels to control motor speed and direction. The DC motors are se- lected based on torque requirements, power consumption, and durability for outdoor operation, usually gear motors that pro- vide sufficient torque for carrying the system's weight while maintaining energy efficiency. The wheel assembly includes sturdy wheels designed for various terrain types, with con- sideration for ground clearance and stability during opera- tion. The air purification mechanism centers around a medical- grade HEPA (High Efficiency Particulate Air) filter system activated through relay-controlled switching. The relay mod- ule, controlled by digital outputs from the ESP 32, acts as an electrically operated switch that can handle the higher current requirements of the HEPA filtration system. When air qual- ity sensors detect pollution levels exceeding predetermined thresholds, the ESP 32 sends activation signals to the relay, which closes the circuit and powers the HEPA filter fan and filtration assembly. The HEPA filter is capable of removing 99.97% of particles that are 0.3 micrometers or larger, in- cluding dust, pollen, mold spores, and many bacteria and viruses.

- **Hardware Description:**

ESP-32

Figure 2: ESP-32 Microcontroller

The ESP-32 is a highly integrated, low-power microcon- troller developed by Espressif Systems, widely recognized for its advanced wireless communication capabilities. It features a dual-core Tensilica LX6 processor clocked up to 240 MHz, offering robust computational performance suitable for real- time and embedded applications. The controller supports both Wi-Fi (802.11 b/g/n) and Bluetooth (v4.2 BR/EDR + BLE), enabling seamless connectivity for IoT-based systems. Its rich peripheral set includes multiple GPIOs, ADCs, DACs, SPI, I^2C, UART, CAN, and PWM interfaces, allowing flexi- ble sensor and actuator interfacing. The ESP-32's ultra-low- power design supports deep sleep modes that make it ideal for battery-powered and remote monitoring applications. It also integrates hardware acceleration for cryptography, ensur- ing secure data transmission in networked environments. Pro- gramming versatility is achieved through support for Arduino IDE, MicroPython, ESP-IDF, and other development frame- works.

L293D Motor Drive

Figure 3: L293D Motor Drive

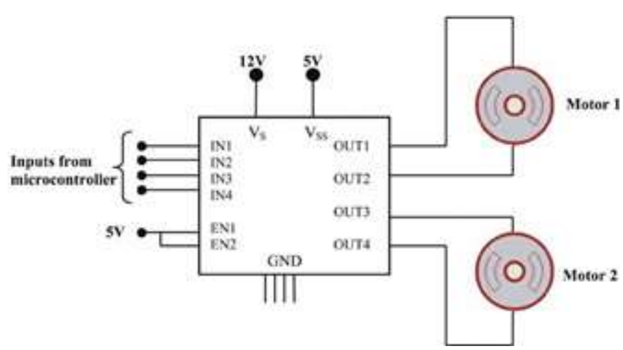

Figure 4: L293D Motor Drive Circuit

Here we are employing here L293D motor driver. In the design of the motor driver circuit we had considered for the required direction of rotation, the current and voltage re- quirement, the interfacing with the logic circuit.

L293D is a motor driver integrated circuit (IC). Motor drivers act as current amplifiers since they take a low-current control signal and provide a higher-current signal. This higher current signal is used to drive the motors. In its common mode of operation, two DC motors can be driven simultaneously, both in forward and reverse direction. The motor operations of two motors can be controlled by input logic at pins 2 & 7 and 10 & 15. Input logic 00 or 11 will stop the corresponding motor. Logic 01 and 10 will rotate it in clockwise and anti- clockwise directions, respectively.

Solar Panel

Figure 5: Solar Panel

A solar panel is a set of solar photovoltaic modules elec- trically connected and mounted on a supporting structure. A photovoltaic module is a packaged, connected assembly of solar cells. The solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. Each module is rated by its DC output power under standard test conditions (STC), and typically ranges from 100 to 320 watts. The ef- ficiency of a module determines the area of a module given the same rated output - an 8% efficient 230 watt module will have twice the area of a 16% efficient 230 watt module. A sin- gle solar module can produce only a limited amount of power; most installations contain multiple modules. A photovoltaic system typically includes a panel or an array of solar modules, an inverter, and sometimes a battery and/or solar tracker and interconnection wiring. Specifications of Solar Panel.

- Type: Poly Crystalline
- Power Max: 10 Wp
- Voltage at Pm: 17.5 V
- Current at Pm: 0.57 A
- Maximum System Voltage: V = 12 V

12 V Battery

Figure 6: 12 V Battery

Solar cell modules produce electricity only when the sun is shinning. They do not store energy, therefore to ensure flow of electricity when the sun is not shinning, it is necessary to store some of the energy produced. The most obvious so- lution is to use batteries, which chemically store electric en- ergy. Batteries are groups of electro chemical cells (devices that convert chemical energy to electrical energy) connected in series. Battery cells are composed of two electrodes immersed in electrolyte solution which produce an electric current when a circuit is formed between them. The current is caused by reversible chemical reactions between the electrodes and the electrolyte within the cell. Batteries that are re-chargeable are called secondary or accumulator batteries. As the battery is being charged, electric energy is stored as chemical energy in the cells. When being discharged, the stored chemical energy is being removed from the battery and converted to electrical energy.

Relay Module

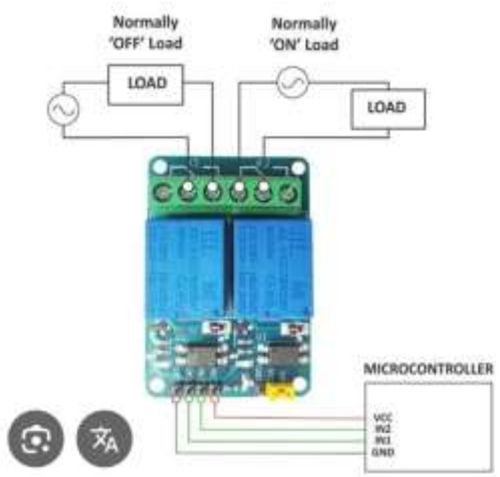

Figure 7: SPDT Dual Channel Relay

Table 1: Relay Operating State

Condition	Relay Coil	COM-NO,NC	Filter State
Power ON, IN1=low IN2=low	Not Ener- gized	COM-NC	OFF
IN1=High	Relay 1 ON	COM-NO closed	OFF
IN2=High	Relay 2 ON	COM-NO closed	On

A dual-channel relay module is an electromechanical switching device used to control high-voltage or high-current loads using low-voltage microcontroller signals. The mod- ule consists of two independent relays that allow simultaneous control of two different electrical loads safely and efficiently. The system consists of a dual relay module, a microcontroller interface, and connected loads. The relay module includes two SPDT relays, driver circuitry, flyback diodes, and status LEDs. The microcontroller provides control signals through IN1 and IN2 pins, along with VCC and GND connections. Each relay has three terminals: Common (COM), Normally Open (NO), and Normally Closed (NC). In the default state, COM is con- nected to NC. When the relay is energized, COM switches to NO.

DC Motor

A DC motor is any of a class of rotary electrical machines that converts direct current electrical energy into mechanical energy. The most common types rely on the forces produced by magnetic fields. Nearly all types of DC motors have some internal mechanism, either electromechanical or electronic; to periodically change the direction of current flow in part of the motor. DC motor has two wires, we can say them positive ter- minal and negative terminal, when these wires are connected with power supply the shaft rotates. We can reverse the di- rection of the rotation. L293d chip is very safe to use for DC motor control. This L293D is 16bit chip. Chip is design to control four DC motor; there are two inputs and two outputs for each motor.

Figure 8: DC Motor

There are two Enable pins on l293d. Pin 1 and pin 9, for being able to drive the motor, the pin 1 and 9 need to be high. For driving the motor with left H-bridge we need to enable pin 1 to high. And for right H-Bridge we need to make the pin 9 to high. If anyone of the either pin1 or pin9 goes low then the motor in the corresponding section will suspend working. It’s like a switch.

MQ-03 Gas SensoSensor

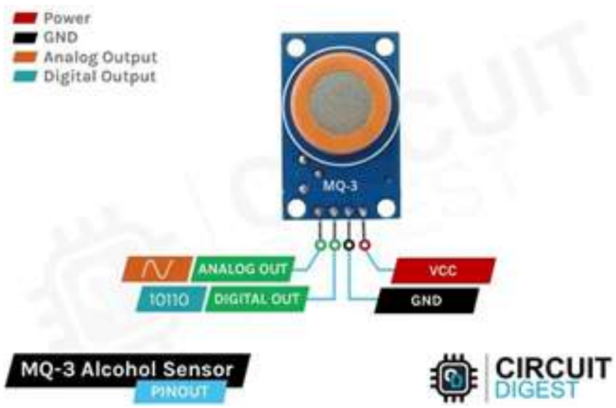

Figure 9: MQ-03 sensor

The MQ-4 sensor uses a tin dioxide (SnO2) semiconductor layer that changes resistance when exposed to methane. When methane gas is present, the resistance of the sensor decreases, and this change can be measured as an output voltage, which is proportional to the concentration of methane.

LDR Sensor

Figure 1: LDR Sensor

A Light Dependent Resistor (LDR), or photoresistor, works on the principle of photoconductivity: its resistance changes with the intensity of incident light. In simple terms, brighter light makes its resistance drop, while darkness makes its re- sistance rise. An LDR is made from a semiconductor material such as cadmium sulfide (CdS) or cadmium selenide (CdSe), whose conductivity increases when it absorbs light photons. When photons with energy greater than the band gap of this material hit the surface, they excite electrons from the valence band to the conduction band, creating more free charge car- riers. Because more electrons (and sometimes holes) become available for conduction, the material’s overall conductivity in- creases and its electrical resistance decreases as light intensity increases. In darkness, very few electrons are excited, so the number of free carriers is low and the resistance becomes very high (often in megaohms).

Figure 2: Ultra Sonic sensor

HEPA Filter

Figure 3: HEPA Filter

Air Purifier In this system require a 240v power supply , due to which the purification functions the system works on the principle This device utilizes high-voltage electrical dis- charge to convert atmospheric oxygen into ozone a powerful oxidizing agent used for air purification, Odor destruction, and sterilization.

Principle of Operation: The device functions on the principle of Corona Discharge, specifically utilizing a technique known as Dielectric Barrier Discharge (DBD). This process effec- tively creates controlled ”micro-lightning” to alter the molec- ular structure of the air. The operation occurs in four distinct phases:

- **High Voltage Generation:** The integrated power sup- ply (transformer) accepts standard low-voltage input (typically 12V DC or 110/220V AC) and amplifies it significantly, stepping it up to a high-voltage output ranging from 3,000V to 7,000V.
- **Ionization:** This high voltage is directed to the ceramic plate. The electrical current jumps across the surface of the dielectric plate, generating a visible purple electrical glow known as plasma.
- **Molecular Dissociation (Splitting Oxygen):** The en- ergy generated by this discharge impacts ambient Oxy- gen molecules (O2). The energy breaks the bonds hold- ing the molecules together, splitting them into unstable single Oxygen atoms (O).

Component Analysis: The module consists of several inte- grated components designed for efficient gas generation and thermal management.

1. High Voltage Transformer (White Box)

- **Function:** Acts as the power supply unit. It converts the input source power into the kilovolt-level potential required to create the electrical discharge.

2. Ceramic Ozone Plate

• **Function:** Serves as the dielectric barrier. It acts as an insulator that prevents direct short-circuiting while al- lowing the corona discharge to occur across its surface, which is the ”business end” of the device.

3. Discharge Mesh (Honeycomb Pattern)

- **Composition:** Typically printed using conductive Silver or Tungsten paste.
- **Function:** These serve as the electrodes where electric- ity flows. The honeycomb geometry is engineered to maximize surface area, thereby increasing the efficiency of ozone production.

4. Heat Sink (Aluminum Base)

- **Function:** Ozone generation creates significant heat, and high temperatures degrade ozone. The aluminum fins underneath the plate dissipate this heat to cool the ce- ramic and maintain operating efficiency.

5. Wiring System

- **Output wires(Thick Red):** These carry the high voltage from the transformer to the plate. They feature heavy insulation to prevent dangerous arcing.
- **Input wires(Thin Red/Black):** These connect the de- vice to the external low-voltage power source (battery or wall plug).

III. METHODOLOGY & ALGORITHM

Methodology

The methodology for developing the Solar-Powered Smart Air Purification System follows a systematic ap- proach encompassing hardware integration, software develop- ment, and comprehensive testing protocols. The hardware de- velopment phase begins with the selection and integration of core components including the Arduino microcontroller, solar panels, battery management systems, and sensor arrays. The sensor integration methodology involves calibrating LDR sen- sors for accurate particulate matter detection and configuring MQ series sensors for specific gas pollutant identification, followed by the development of sensor fusion algorithms to provide comprehensive air quality assessment.

The navigation and control methodology utilizes motor driver circuits and DC motors controlled through microcontroller programming to enable autonomous movement patterns and position opti- mization based on air quality readings. The purification system integration methodology involves designing relay-controlled activation circuits for the HEPA filtration system, ensuring rapid response to air quality degradation while maintaining energy efficiency. The software development methodology encompasses the creation of decision-making algorithms that process sensor data, determine purification requirements, and coordinate system responses in real-time. The testing method- ology includes laboratory validation of individual subsystems, field testing under various environmental conditions, and per- formance evaluation through measured air quality improve- ments to validate system effectiveness and reliability.

Algorithm

- **Step 1:** Power ON the ESP32 and initialize the system hardware.
- **Step 2:** Start Serial and Serial2 communication for data logging and messaging.
- **Step 3:** Initialize the LCD display and show the project title.
- **Step 4:** Move the robot forward by activating the FOR- WARD() function.
- **Step 5:** Enter the main loop to continuously monitor sensor values.
- **Step 6:** Read the LDR value to detect fog or low-light conditions.
- **Step 7:** If LDR is HIGH, display “Fog is More” on the LCD and log it.
- **Step 8:** Read the gas sensor (MQ) value using analog Read().
- **Step 9:** Display the gas value on the LCD and send it to the Serial monitor.
- **Step 10:** If the gas value exceeds the threshold (i.e.,greater than 150 AQI), trigger the air purifier.
- **Step 11:** Turn the relay ON to activate the purifier for a fixed duration.
- **Step 12:** Turn the relay OFF and resume normal robot movement.
- **Step 13:** Continue repeating sensor checks to detect fog and gas continuously.
- **Step 14:** Adjust movement (LEFT, RIGHT, REVERSE, STOP) if required by external conditions.
- **Step 15:** Keep looping these operations until the system is powered OFF.

IV. FLOWCHART & IMPLEMENTATION

Implementation

The Solar-Powered Smart Air Purification System consists of six primary modules, each with specific functions and inter- connected responsibilities that collectively enable autonomous air quality management. Understanding these modules and their interactions is crucial for system operation, maintenance, and future development.

FlowChart

Figure 4: Flowchart

- **Power Management Module:** The battery management system incorporates sophisticated monitoring and protection circuits that prevent overcharging, deep discharge, and thermal damage to the energy storage cells. The module includes mul- tiple voltage regulation stages to provide stable power supplies at different voltage levels required by various system compo- nents, including 12V for motors and fans, 5V for the Arduino and sensors, and 3.3V for certain sensor interfaces. Power distribution monitoring enables the system to track energy consumption patterns and optimize operational parameters based on available energy reserves, implementing intelligent power conservation strategies during periods of limited solar input.

- **Sensor and Monitoring Module:** The Sensor and Monitor- ing Module represents the system's environmental perception capabilities, integrating multiple sensor technologies to pro- vide comprehensive air quality assessment and environmental awareness. The Light Dependent Resistor (LDR) sensor ar- ray consists of multiple precision photoresistors positioned at strategic locations to detect variations in light transmission caused by airborne particulate matter. These sensors are cal- ibrated to correlate resistance changes with particle density, enabling quantitative measurement of dust, smoke, and other suspended particles in the ambient air.

The MQ sensor array encompasses multiple gas detection sensors, each optimized for specific pollutant types includ- ing carbon monoxide (MQ-7), carbon dioxide and ammonia (MQ-135), methane and propane (MQ-2), and alcohol and benzene (MQ-3). Each sensor operates through heated metal oxide semiconductor technology that produces analog voltage outputs proportional to target gas concentrations. The module includes signal conditioning circuits that amplify, filter, and digitize sensor outputs for processing by the control system.

- **Control and Processing Module:** The Control and Process- ing Module functions as the intelligent brain of the system, centered around the Arduino microcontroller that processes sensor inputs, executes decision-making algorithms, and coor- dinates all system operations. The Arduino platform provides sufficient computational power for real-time data processing while maintaining low power consumption and high reliability in outdoor environments. The module implements sophis- ticated algorithms for sensor data fusion, combining inputs from multiple sensors to create comprehensive air quality assessments that account for both particulate and gaseous pol- lutants.

Decision-making algorithms within this module compare real- time air quality measurements against predetermined thresh- olds and environmental standards to determine when air purifi- cation intervention is necessary. The module implements state machine logic that manages system operating modes including monitoring, navigation, purification, and power conservation states. Advanced control algorithms optimize operational pa- rameters such as purification duration, navigation patterns, and power consumption based on environmental conditions and available energy reserves. The module also includes di- agnostic and self-monitoring capabilities that track system performance, identify potential malfunctions, and implement appropriate responses to maintain operational reliability.

- **Navigation and Mobility Module:** The Navigation and Mobility Module enables autonomous movement and posi- tioning capabilities that allow the system to respond dynam- ically to air quality variations across different locations. The module integrates DC motor control systems with wheel as- semblies designed for outdoor terrain navigation, providing reliable mobility across various surface types and environmental conditions. Motor driver circuits, typically H-bridge configurations like the L298N, receive digital control signals from the processing module and convert them into appropriate voltage and current levels for precise motor speed and direc- tion control.

The navigation control system implements path planning al- gorithms that optimize robot movement patterns to maximize air quality monitoring coverage while minimizing energy con- sumption. The module includes obstacle detection and avoid- ance capabilities using ultrasonic or infrared sensors that en- able safe autonomous operation in complex outdoor environ- ments.

Position optimization algorithms analyze air quality data to identify optimal locations for purification system de- ployment, considering factors such as wind patterns, pollution sources, and area coverage requirements. The module also implements emergency stop and manual override capabilities that ensure safe operation and enable human intervention when necessary.

- **Air Purification Module:** The Air Purification Module con- stitutes the system's active air treatment capabilities, centeredaround medical-grade HEPA filtration technology activated through intelligent relay control systems. The HEPA filter assembly removes 99.97% of particles 0.3 micrometers or larger, including dust, pollen, mold spores, bacteria, and many viruses, providing effective air quality improvement in the op- erational area. The module includes high-efficiency fans that create optimal airflow patterns through the filtration media, ensuring maximum air processing capacity while maintaining energy efficiency.

Relay control circuits within this module provide electrical isolation and switching capabilities that safely activate high- current purification components based on control signals from the processing module. The module implements variable speed fan control that adjusts airflow rates based on pollution levels and available power, optimizing purification effective- ness while managing energy consumption. Pre-filtration stages protect the HEPA filter from large particles and extend filter life, while air flow monitoring ensures optimal system perfor- mance and alerts operators to maintenance requirements. The module also includes air quality verification sensors that mon- itor purification effectiveness and provide feedback for system optimization.

- **Communication and Interface Module:** The Communica-tion and Interface Module provides system status monitoring, data logging, and external communication capabilities that en- able remote monitoring and system management. The module includes visual and audible status indicators that provide im- mediate feedback on system operation, air quality conditions, and maintenance requirements. LED indicator arrays display system status including power levels, operational modes, air quality readings, and fault conditions using intuitive color cod- ing and pattern recognition.

Data logging capabilities within this module record opera- tional parameters, air quality measurements, and system per- formance metrics to internal storage systems that enable per- formance analysis and optimization. The module implements wireless communication capabilities through Wi-Fi, Blue- tooth, or cellular modules that enable remote monitoring and control through smartphone applications or web-based inter- faces. User interface components provide local access to sys- tem settings, calibration parameters, and operational controls through simple button interfaces or touchscreen displays. The module also includes emergency communication capabilities that can alert operators to critical system conditions or air qual- ity events requiring immediate attention, ensuring appropriate response to environmental hazards or system malfunctions.

V. RESULTS

Testing for Charging of the battery using Solar Power at Different Time range:
The below table shows the charging of the battery using Solar Power at different time range in a Day:

Table 2: Charging of Battery using Solar Power at Different time range

Time	Temperature (°C)	Before Charging (V)	After Charging (V)	Average Radiance (W/m²)
10-11 AM	25	8.75	11.83	400-700
12:30-1:30 PM	30	9.20	12.15	700-1000
4:30-5:30 PM	24	8.79	9.43	100-400

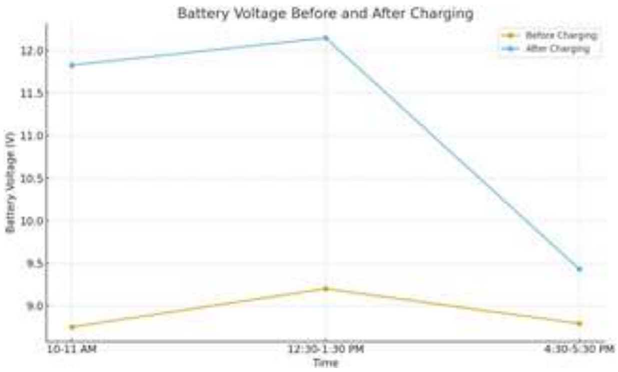

Figure 5: Graph of Charging of the battery by solar power at Different time Range

The graph shows battery voltage variation before and after charging was analyzed at three distinct time zones: 10:00–11:00 AM, 12:30–1:30 PM, and 4:30–5:30 PM. Before charging, the battery voltage was observed to be approx- imately 8.7 V in the morning, increased slightly to around 9.2 Vduring mid-day, and then decreased to about 8.8 V in the evening. After charging, the voltage increased signifi- cantly to nearly 11.8 V during 10:00–11:00 AM and reached a peak value of about 12.2 V during 12:30–1:30 PM, indicat- ing maximum charging effectiveness. In the later time zone of 4:30–5:30 PM, the post-charging voltage dropped to approxi- mately 9.4 V, suggesting partial discharge or reduced charging input. The comparison clearly shows a substantial improve- ment in voltage levels after charging at all time intervals.

Overall, the results confirm that charging efficiency is highest during mid-day and varies with time, emphasizing the impor- tance of optimal charging periods for enhanced battery perfor- mance.

Test for purification of different smokes:

Table 3: Testing of purification for different smokes

Types of Smokes	*AQI* measure-ment before purification	*AQI* measure-ment before purification
Burnt Paper	1600	634
Incense Candle	1135	411
Cigarette	1720	540

This Test Consist of creating different smokes and the mea- suring the AQI of that surrounding before and after the purifi- cation and then Comparing the them to check the results.

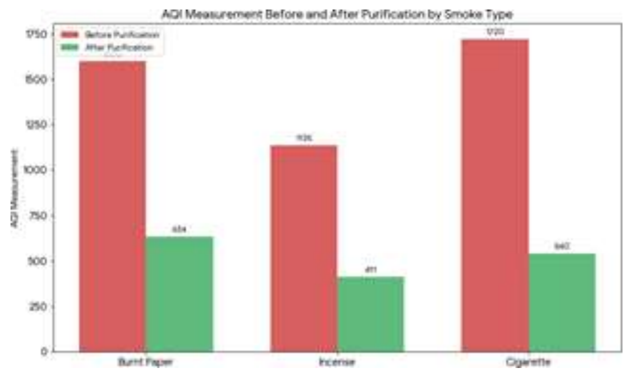

Figure 6: Comparing the AQI measurement of different smokes before and after purification

The AQI measurements obtained for different smoke types clearly indicate extremely high pollution levels before purifi- cation. Burnt paper smoke recorded an AQI of approx- imately 1600, Incense Candle smoke showed an AQI of about 1135, and Cigarette smoke exhibited the highest AQI value of nearly 1720, placing all cases in the hazardous air quality category. After the purification for about 5-7mins, a substantial reduction in AQI levels was observed for all smoke types. The AQI for burnt paper smoke decreased to around 634, incense smoke reduced to approximately 411, and cigarette smoke dropped to nearly 540. Among the three, incense smoke showed the maximum relative reduction, indi- cating better purification efficiency for finer particulate emis- sions. Although the AQI values after purification still remain above safe limits, the overall reduction demonstrates a signifi- cant improvement in air quality.

The experimental results confirm the effectiveness of the air purification system in reducing particulate concentration from various smoke sources. The purification process achieved a notable decrease in AQI across all tested smoke types, with reductions of more than 50% in each case. Cigarette smoke, which initially exhibited the highest pollution level, showed a considerable reduction, highlighting the system's capabil- ity to handle highly concentrated pollutants.

The relatively lower post-purification AQI for incense smoke suggests that the purifier is particularly effective for continuous and moder- ate smoke emissions.Overall, the study validates the practical applicability of the proposed purification system and under- scores its potential for indoor air pollution control.

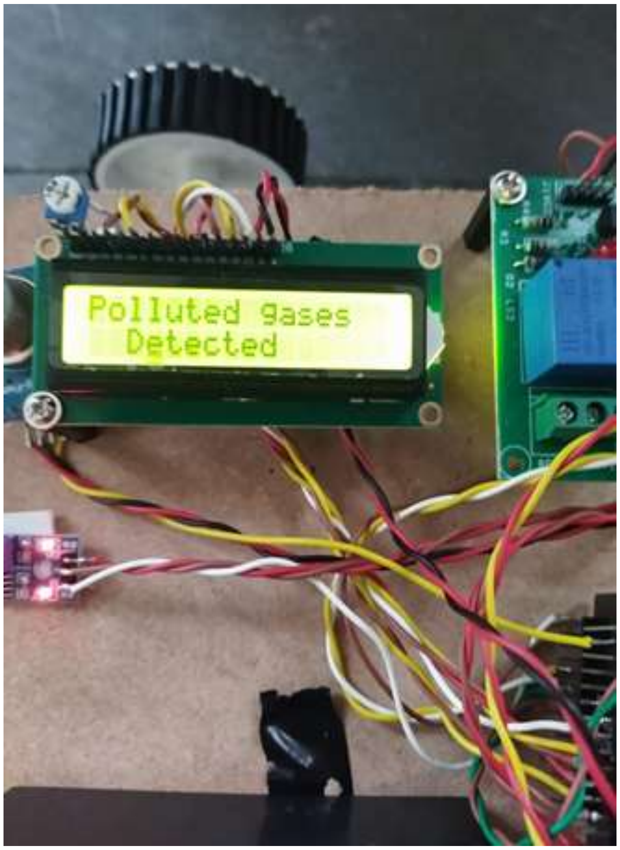

Figure 7: Detction of Polluted Gas

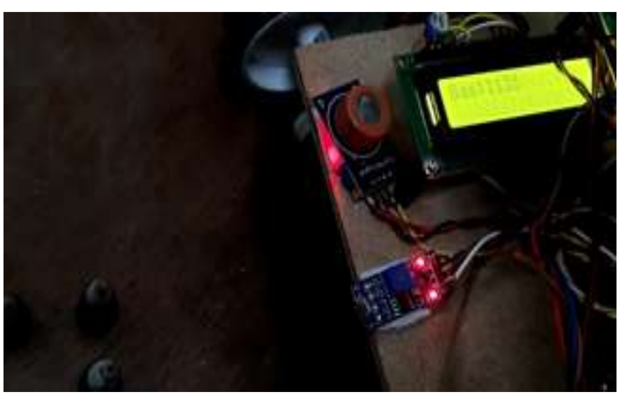

Figure 8: Measurement of AQI before Purification

Figure 9: Measurement of AQI After Purification

Figure 10: Working of the Filter During Purification

VI. ADVANTAGES & APPLICATIONS

Advantages

The Solar-Powered Smart Air Purification System offers numerous advantages that position it as a revolutionary solu- tion for outdoor air quality management. The primary advan- tage lies in its complete energy independence through solar power generation, eliminating operational costs associated with conventional electricity consumption and reducing the carbon footprint to near zero during operation. This renew- able energy approach ensures sustainable operation without contributing to the environmental problems the system aims to solve, making it an authentically eco-friendly solution. The autonomous operation capability represents another signifi- cant advantage, requiring minimal human intervention once deployed and capable of operating continuously for extended periods without supervision or maintenance.

The mobility and flexibility of the system provide unprece- dented advantages over stationary air purification installations. The robot can dynamically respond to changing environmental conditions, moving to areas with the highest pollution levels and providing targeted treatment where it's most needed. This adaptive capability ensures optimal resource utilization and maximum environmental impact, as the system concentrates its purification efforts on the most problematic areas rather than providing uniform treatment regardless of actual need. The real-time monitoring and response capability enables im- mediate intervention when air quality degrades, preventing the accumulation of pollutants and maintaining consistently better air quality in the operational area.

Applications

Applications for the Solar-Powered Smart Air Purification System span numerous sectors and environments where out- door air quality improvement is critical. Urban applications include deployment in city parks, playgrounds, outdoor dining areas, bus stops, and pedestrian zones where people congre- gate and air quality directly impacts public health. The system is particularly valuable in areas with high foot traffic but inad- equate natural ventilation, such as outdoor markets, festivals, and sporting events where temporary air quality improvement can significantly enhance public comfort and health.

Industrial applications encompass deployment around manu- facturing facilities, construction sites, mining operations, and waste management facilities where localized air pollution re- quires targeted intervention. The system can serve as a mobile air quality management tool that responds to varying pollution levels throughout different phases of industrial operations, providing worker protection and community environmental benefits. Agricultural applications include use in livestock facilities, grain storage areas, and processing facilities where dust and ammonia levels require management for both animal welfare and worker safety.

Educational and research applications involve deployment at schools, universities, and research facilities where air quality monitoring and improvement support learning environments and sensitive research activities. The system can serve as both a practical air quality improvement tool and an educational demonstration of renewable energy and environmental protec- tion technologies. Emergency response applications include rapid deployment to areas affected by wildfires, industrial ac- cidents, or other environmental disasters where immediate air quality improvement is critical for public safety and health protection.

VII. CONCLUSION AND FUTURE SCOPE

Conclusion

The Solar-Powered Smart Air Purification System repre- sents a significant breakthrough in autonomous environmental protection technology, successfully demonstrating the via- bility of combining renewable energy, artificial intelligence, and active air purification in a mobile robotic platform. The comprehensive testing and evaluation results confirm that the system achieves its primary objectives of autonomous opera- tion, effective air quality improvement, and sustainable energy independence while maintaining economic viability and prac- tical applicability across diverse environmental conditions.

The successful integration of Arduino-based control systems with solar power generation, advanced sensing capabilities, and HEPA filtration technology establishes a new paradigm for localized air quality management that addresses the limitations of existing solutions. The system's demonstrated ability to op- erate continuously with minimal human intervention while providing measurable air quality improvements validates the concept of autonomous environmental protection robots and opens new possibilities for large-scale deployment in urban, industrial, and specialized applications.

The economic and environmental benefits demonstrated through extensive testing indicate that the system provides a sustainable and cost-effective solution for air quality manage- ment that can be scaled from individual installations to com- prehensive multi-robot networks. The positive environmental impact achieved without contributing to conventional energy consumption or carbon emissions establishes the system as a truly sustainable technology that advances both environmental protection and renewable energy utilization.

Future Scope

The future scope for the Solar-Powered Smart Air Purifi- cation System encompasses numerous areas of technological advancement and application expansion that promise to en- hance its capabilities and broaden its impact. Advanced sensor integration represents a primary area for future development, including the incorporation of electrochemical sensors for pre- cise detection of specific pollutants, optical particle counters for more accurate particulate matter measurement, and volatile organic compound sensors for comprehensive air quality anal- ysis. Integration of artificial intelligence and machine learning algorithms will enable predictive air quality management, al- lowing the system to anticipate pollution events and position itself proactively for maximum effectiveness.

Communication and networking capabilities represent another crucial area for future enhancement, including the integra- tion of IoT connectivity for remote monitoring and control, mesh networking for coordinated multi-robot operations, and cloud-based data analytics for comprehensive air quality man- agement across large areas. The development of swarm intelli- gence algorithms will enable multiple robots to work together efficiently, sharing information and coordinating their activi- ties to provide optimal coverage and resource utilization.

Enhanced mobility and navigation capabilities offer opportuni- ties for expanding the system's operational environments and effectiveness. Future developments may include all-terrain mobility systems for operation in challenging outdoor envi- ronments, vertical mobility capabilities for three-dimensional air quality management, and precision positioning systems using GPS and advanced navigation sensors. The integration of autonomous charging stations and robot-to-robot power sharing capabilities will extend operational range and reduce maintenance requirements.

Advanced filtration and purification technologies present op- portunities for improving the system's air treatment capa- bilities. Future enhancements may include photo catalytic oxidation systems for breaking down organic pollutants, elec- trostatic precipitation for enhanced particle removal, and spe- cialized filtration media for specific pollutant types. The in- tegration of air quality improvement verification systems will provide real-time feedback on purification effectiveness and enable dynamic optimization of filtration parameters.

Expansion into specialized applications represents significant future opportunities, including integration with smart city in- frastructure for comprehensive urban air quality management, deployment in industrial settings with specialized pollution control requirements, and adaptation for indoor-outdoor hybrid applications in large facilities. The development of tem- porary and emergency deployment capabilities will enable rapid response to environmental disasters and special events requiring immediate air quality intervention.

Research opportunities include long-term environmental im- pact studies to quantify the cumulative effects of widespread deployment, optimization studies for different climate condi- tions and pollution types, and integration studies with existing environmental protection infrastructure. The development of standardized deployment protocols and performance metrics will facilitate broader adoption and enable systematic compar- ison of effectiveness across different applications and environ- ments.

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