



Solar-Assisted Intelligent Street Cleaning Robot

Ahlaya A¹, Ardra Krishna C^{2*}, Aditya Kalathil³, Asna K. H⁴, Mredhula L⁵

^{1,2,3,4} UG Scholar, Nehru College of Engineering and Research Centre, Kerala, India

⁵ Head of Department, Nehru College of Engineering and Research Centre, Kerala, India

* Email ID: nce23ec015@ncerc.ac.in

ARTICLE INFO

Article type:

Research Article

Article history:

Received: 28-07-2026

Received in revised form:

19-08-2026

Accepted: 20-08-2026

Available online: 20-08-2026

Keywords:

Bluetooth Control

ESP32 Microcontroller

Photovoltaic Solar Panel

Renewable Energy

Smart Street Cleaning

Ultrasonic Sensor

ABSTRACT

Rapid urbanization has increased street-level waste, while conventional cleaning remains labour-intensive and fuel-dependent. This paper presents a Solar-Assisted Intelligent Street Cleaning Robot that automates cleaning with renewable energy. An ESP32 microcontroller is operated wirelessly through a Bluetooth mobile application. Power comes from a 12V photovoltaic panel and rechargeable Li-ion battery via a DC-DC buck converter, supporting battery operation with solar-assisted charging. Four DC geared motors drive locomotion and two power rotary brushes; an HC-SR04 ultrasonic sensor provides real-time obstacle detection. Outdoor trials on a 20 m² area showed 88% cleaning coverage (17.6 m²), 95% obstacle-avoidance (19 of 20 trials) at a 20 cm threshold, about 90% removal of light debris (dust and paper), and average power of 38 W over 30 minutes (approximately 19 Wh). The prototype combines solar operation, wireless control, and obstacle avoidance for energy-conscious, low-labour street cleaning.

1. INTRODUCTION

The booming urbanization and the growth of population have resulted in a considerable number of wastes in the streets and public places, making efficient cleaning an important challenge. Traditional street cleaning practice is primarily manual labor and fuel powered equipment, which is time consuming, labor intensive and pollutes the environment. These constraints emphasize the need for an automated, energy-efficient and eco-friendly cleanliness system.

Solar-Assisted Intelligent Street Cleaning Robot is a proposed robot that will clean the roads automatically with a solar-powered cleaning head. This system is powered by a rechargeable battery with power generated by a photovoltaic solar panel, and controlled by an esp32 microcontroller. The robot can be controlled via the user's mobile application, which is Bluetooth capable, which means that the user can control the robot's movement wirelessly. The four DC geared motors are used for the locomotion and the two more are used to rotate the cleaning brushes.

An HC-SR04 ultrasonic sensor continuously senses the obstacles to guarantee safe navigation without collision. The proposed system, which has been integrated with the use of renewable energy, embedded control, wireless communication and obstacle detection, is a cost-efficient and environmentally friendly way of cleaning streets, pavements and other public spaces. The robot eliminates manual labor, cuts operating expenses and enables sustainable urban maintenance. Besides, the proposed system could serve as a solid basis for future smart cleaning technologies. It can be scaled up for larger public areas and be incorporated into the smart city infrastructure for fully automated urban upkeep with further enhancements

2. LITERATURE REVIEW

Two tracks of robotic cleaning systems research have emerged, one for the maintenance of solar panels, and another for street/floor sweeping robots, either of them being autonomous or semi-autonomous Robots for cleaning solar panels. There is also a considerable amount of research devoted to robot systems which clean photovoltaic panels, not streets.

Dedicated solar-panel cleaning robots were proposed by Hashim et al. and Santosh Kumar et al. to keep the PV efficiency up by cleaning the PV panels to remove the accumulation of dust [1, 2]. Sandey et al. and Roy et al. modified this idea, using mechanical simplifications and low-cost mechanical designs [3, 4]. Jaradat et al. were able to present a fully portable robotic system for cleaning which was capable of being used for cleaning panel, whereas Ronnaronglit and Maneerat developed a cleaning platform having a main thrust on the mobility of the robotic system across the panel arrays [5, 6]. In recent years, Amin et al. integrated the drone and ground-based robotic systems with AI-based control for both cleaning and predictive maintenance, moving beyond mechanical cleaning to intelligent, sensor-driven maintenance [7]. Sweeping/floor-cleaning robots that are autonomous or controlled by apps. The second stream of research focuses on the cleaning of streets and floors, not solar infrastructure. An early trial of autonomous street sweeping that involved crabwalking to the curb was reported by Jeon et al., which underscores the challenges of navigating and operating the outdoor sweeping task [8]. Murdan and Ramkissoon designed a smart autonomous cleaning robot that is controlled via an application running on the Android phone, which proves that the application-based wireless control of cleaning robots is possible [9]. Khan et al. have created a smart and solar-powered street sweeping machine, which directly integrates the smartness of electricity generated by solar power [10]. In 2023, Kiran Kumar et al. suggested a solar powered dry waste segregator robot that took solar assisted sweeping a step further towards waste segregating [11]. Gap addressed by this work. The existing solar-panel cleaning robots are not designed for general street or pavement cleaning, and the existing street-sweeping robots for instance the Jeon et al. and the Murdan and Ramkissoon platforms are mostly grid-powered or battery-only powered models and few quantitative obstacle avoidance or coverage metrics are reported [8, 9]. The most similar vehicle is the Khan et al. solar-powered sweeper, but it does not detail the ultrasonic obstacle-detection capabilities or Bluetooth-app control [10]. In this work, solar-assisted power management, embedded control with ESP32, and Bluetooth smartphone control in a low-cost prototype of a street-cleaning robot are integrated with the obstacle avoidance system using ultrasonic sensors (HC-SR04), which has quantitative evaluation of coverage (88%), energy consumption (≈ 19 Wh/30 min) and obstacle-avoidance success rate (95%).

3. MATERIALS AND METHODS

The Solar-Assisted Intelligent Street Cleaning Robot was proposed to solve the problems of street cleaning using robots by providing an environmentally friendly and automated solution. This system combines the effective utilization of renewable energy, solar power, embedded control, wireless communication, and obstacle detection to clean efficiently and with minimal human involvement. The hardware architecture consists of an ESP32 microcontroller, motor driver modules, DC geared motors, an ultrasonic sensor, a photovoltaic solar panel, a rechargeable battery, and a cleaning mechanism. The software is programmed in the Arduino IDE for the robot's movement, cleaning operation and the obstacle detection.

3.1 Materials

The hardware components used in the development of the proposed system are listed in **Table 1**.

Table 1. Hardware Components Used

Component	Specification	Quantity
ESP32 Development Board	ESP-WROOM-32	1
L298N Motor Driver Module	Dual H-Bridge	2
DC Geared Motors (Wheel Drive)	12V	4
DC Geared Motors (Cleaning Brush)	12V	2
Robot Wheels	Rubber Wheels	4
Cleaning Brushes	Rotary Brush	2
HC-SR04 Ultrasonic Sensor	2–400 cm	1
Solar Panel	12 V Photovoltaic Panel	1

Component	Specification	Quantity
Rechargeable Battery Pack	12 V Li-ion	1
DC-DC Buck Converter	XL4015	1
Robot Chassis	Four-wheel platform	1

3.2 System Design

The circuit diagram for the proposed Solar-Assisted Intelligent Street Cleaning Robot is shown below. As shown in the circuit diagram, the Solar-Assisted Intelligent Street Cleaning Robot has two L298N motor driver modules, six DC geared motors, an HC-SR04 ultrasonic sensor, a photovoltaic solar panel, a rechargeable battery, and an ESP32 microcontroller.

The ESP32 is used as the main controller of the system. It is instructed by a Bluetooth wireless app on a mobile device and drives the motors using two motor driver modules L298N. The robot uses four DC geared motors for its locomotion and two more DC motors to drive the rotating cleaning brush. The HC-SR04 ultrasonic sensor is connected to the ESP32 to detect obstacle in front of the robot. If the robot gets into a collision with an obstacle within a safety distance predefined by the controller, the robot is automatically stopped during forward motion to avoid collision. It is comprised of PV solar module, rechargeable battery and a DC-DC buck converter. The solar panel charges the battery and the buck converter supplies the regulated voltage to the ESP32 and other electronic components. The photovoltaic subsystem supports battery charging and can extend the operating capability of the robot under suitable solar conditions. Continuous operation depends on the battery capacity, solar irradiance, charging efficiency, and electrical load.

Embedded control, wireless communication, obstacle detection and solar power energy management offer an effective and eco-friendly solution for automated street cleaning. The whole hardware connections of the proposed system are depicted in **Figure 1**.

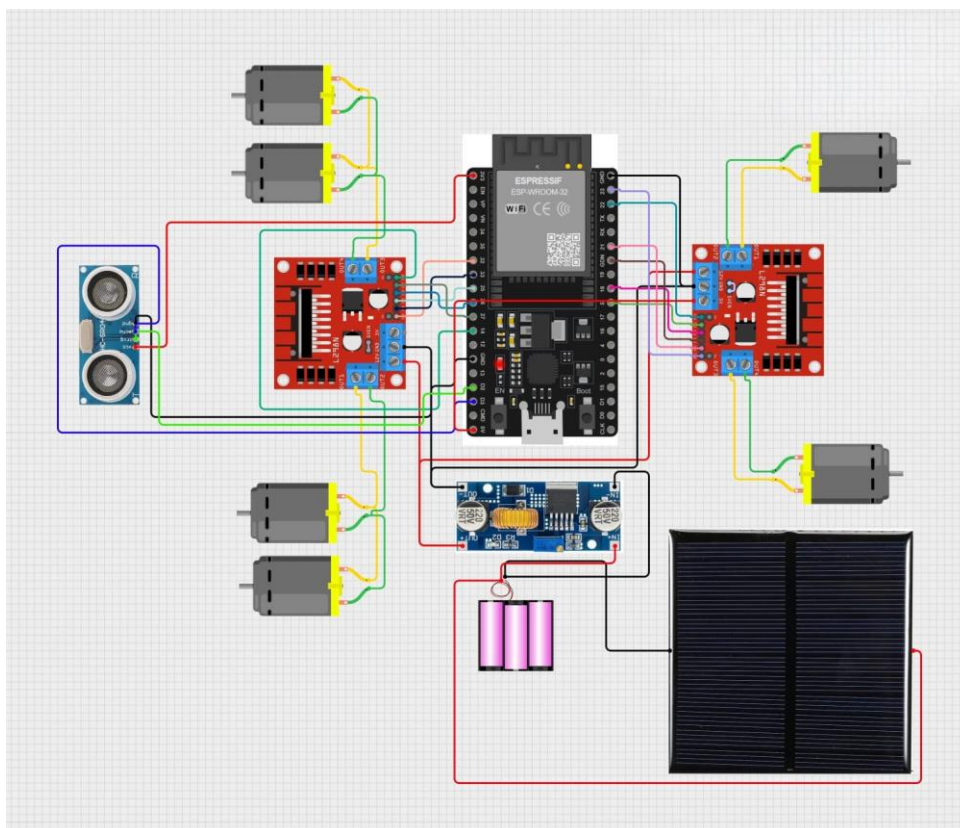


Figure 1. Circuit diagram of the proposed Solar-Assisted Intelligent Street Cleaning Robot

3.3 Software Implementation

The Arduino IDE software has been used to develop the software for the proposed Solar-Assisted Intelligent Street Cleaning Robot. The main controller in the system is the ESP32 microcontroller. It is controlled by the mobile application and acts as a connection between the robot and the motors and sensors attached to it. The robot will be controlled using a mobile app that can be connected via Bluetooth.

The commands are: F: Forward, B: Backward, L: Left, R: Right, and S: Stop. The commands M and N are used to turn the cleaning brush motors ON and OFF. Using these commands, the ESP32 drives the motor drivers and makes the robot go in the direction it is intended. The HC-SR04 ultrasonic sensor is continuously monitoring for obstacles in front of the robot. The ESP32 automatically stops moving when it detects an obstacle within 20 cm, it will pause the robot to prevent colliding. This increases the safety and reliability of the system during operation.

The software continuously reads in the user commands and sensor data in a loop. It also transmits the distance measured to the mobile application for monitoring via Bluetooth. A simple control program that provides smooth robot movement, efficient cleaning and reliable performance.

3.4 Working Methodology

The working methodology of the proposed Solar-Assisted Intelligent Street Cleaning Robot is shown in **Figure 2**.

The solar panel generates electricity from sunlight, charging the rechargeable battery. The battery is connected to the ESP32 microcontroller, motor drivers and other electronic components via a DC-DC buck converter. It reads the instructions of robot movement from the mobile application that uses Bluetooth technology and passes them on to the L298N motor driver modules which control the robot. F, B, L, R and S represent Forwards, Backwards, Left, Right and Stop, respectively. M and N are used to start and stop the cleaning brush motors. The rotating brushes gather dust and other light debris in the path of the robot as it travels.

The HC-SR04 ultrasonic sensor is used to continuously sense an obstacle in front of the robot. The ESP32 automatically halts the robot when it detects an obstacle when it is moving forward within 20 cm to avoid collision. Therefore, the proposed system is an efficient, safe and environmentally friendly automated street cleaning system.

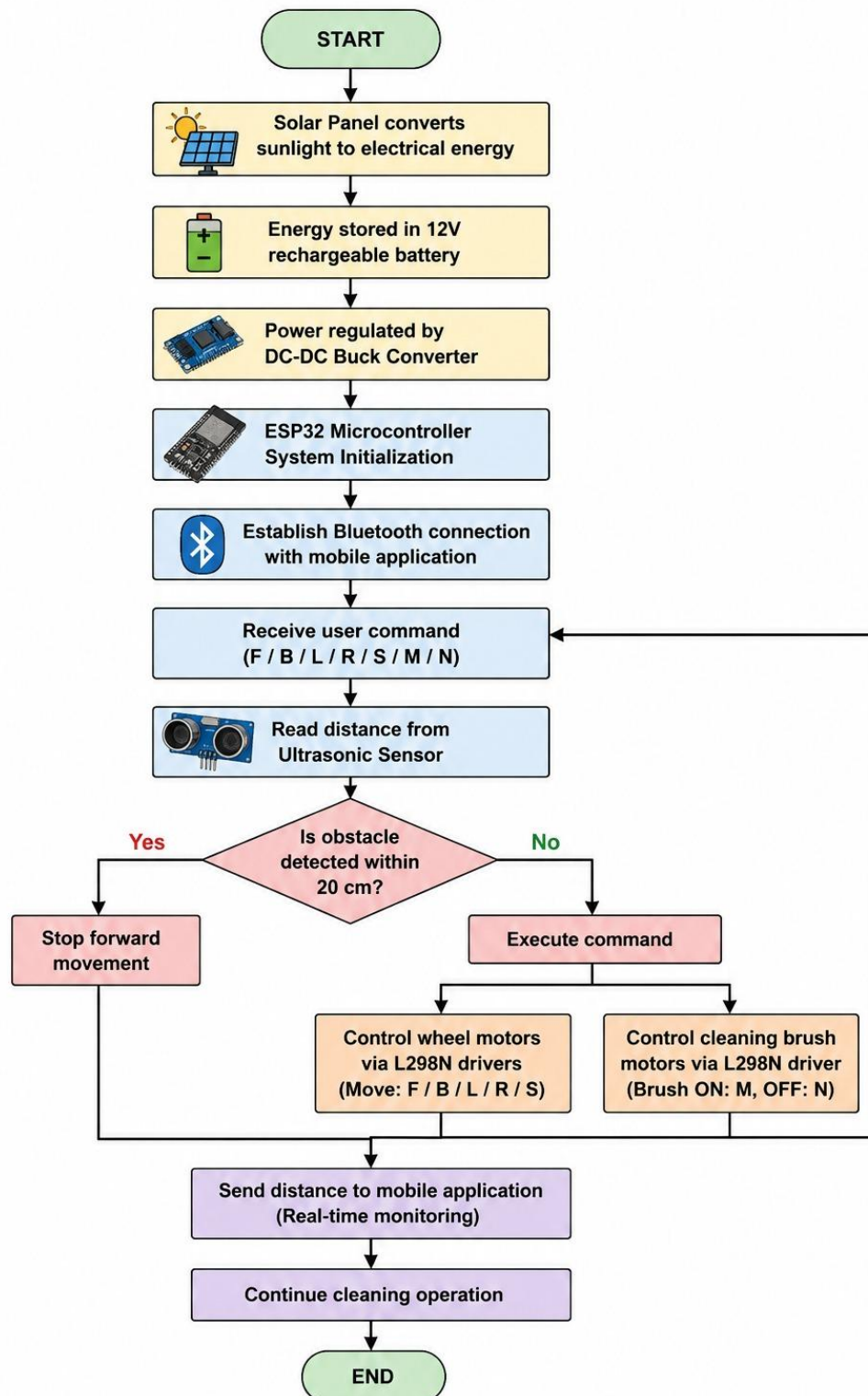


Figure 2. Working methodology (flowchart) of the proposed Solar-Assisted Intelligent Street Cleaning Robot

4. RESULTS AND DISCUSSION

It was successfully designed and tested in small scale outdoor test conditions for the proposed Solar-Assisted Intelligent Street Cleaning Robot. The robot was able to move smoothly and reliably on the

instructions F (Forward), B (Backward), L (Left), R (Right), S (Stop), M (Brush ON), and N (Brush OFF) that were given via the Bluetooth transmitter. The cleaning brush motors were good at clearing dust, paper, and similar materials which are light materials from the ground. The HC-SR04 ultrasonic sensor was able to detect an obstacle inside its range (20 cm) and at the same time stop the robot when it was moving forward, thus preventing it from colliding. With sufficient sunlight, the solar panel could recharge the rechargeable battery enabling energy-efficient operation. The overall performance of the proposed system is summarised in **table 2**.

Table 2. Performance Evaluation of the Proposed System

Parameter	Observed Result
Robot movement	Stable
Bluetooth communication	Reliable operation
Obstacle detection	Successful within 20 cm
Cleaning performance	Effective for dust and debris
Solar charging	Battery charged under adequate sunlight

4.1 Quantitative Performance Evaluation

To quantitatively evaluate the performance of the proposed Solar-Assisted Intelligent Street Cleaning Robot, experiments were conducted over a small outdoor test area. The robot was tested on a 20 m² area, of which approximately 17.6 m² was effectively covered and cleaned, resulting in a coverage of **88%**. The average operating time during the test was approximately 30 minutes, with an average power consumption of 38 W. Thus, the estimated energy consumed during a complete test was approximately 19 Wh.

The obstacle avoidance capability was evaluated using 20 obstacle trials. The ultrasonic sensor successfully detected and stopped the robot before collision in 19 out of 20 trials, resulting in an obstacle success rate of 95%. The obstacle detection threshold was maintained at approximately 20 cm, consistent with the control algorithm implemented using the HC-SR04 ultrasonic sensor.

The cleaning efficiency was also evaluated using light materials such as dust and small paper debris. Approximately 90% of the targeted light debris was removed from the test path. These results demonstrate that the prototype provides satisfactory area coverage, low energy consumption and reliable obstacle detection for small-scale outdoor cleaning applications. **Table 3** presents quantitative performance evaluation of the proposed system.

Table 3. Quantitative Performance Evaluation of the Proposed System

Parameter	Measured Result
Test area	20 m ²
Effective cleaned area	17.6 m ²
Coverage	88%
Average operating time	30 min
Average power consumption	38 W

Experimental results show that the proposed system can be used to clean small-scale streets efficiently and in an environmentally friendly way. The combination of solar power, embedded control, Bluetooth communication, and obstacle avoidance minimized human intervention and provided safe and reliable operation. The existing prototype can be used, however, for light debris and small outdoor spaces. In the future, the autonomous navigation, monitoring using IoT, and improved cleaning mechanism can be targeted to increase the overall efficiency and applicability of the system.

Beyond the prototype scale, AI-assisted automation continues to expand across technology sectors, with evidence that AI adoption improves operational performance in information-technology-intensive work [12]. At the same time, as autonomous agents move into public infrastructure and everyday services, the governance of algorithmic agency becomes a design consideration for future smart-city deployments of platforms such as the one developed in this work [13].

5. CONCLUSION

The Solar-Assisted Intelligent Street Cleaning Robot was designed, implemented as a prototype and experimentally tested to apply to the small-scale cleaning in the outdoor environment, which combined an ESP32 microcontroller, a Bluetooth control system, rotary cleaning brushes, an ultrasonic sensor (HC-

SR04), a photovoltaic (PV) panel, a rechargeable battery, and a motor-drive system. It was observed that the prototype cleaned 88% surface with a power consumption of around 38 W on average (≈ 19 Wh in 30 min of operation) with a 95 % success rate of obstacle avoidance (19 out of 20 trials, with a detection threshold of 20 cm) and good cleaning results, especially for light debris like dust and paper. The results confirm the technical viability of the prototype for cleaning light debris in small scale but it is not a fully autonomous system as the navigation is mainly controlled via Bluetooth and there has not been demonstrated the continuous operation of the system from self-power using solar power under different environmental conditions. Future work includes autonomous navigation, multiple sensor-based obstacle detection, assistance with monitoring and relying on the Internet of Things, better debris collection, optimization of solar energy and tests with different surfaces, debris, weather, and expanded test areas with repeated tests and statistical analysis.

The current prototype has several limitations. The robot is primarily Bluetooth-controlled and therefore does not provide fully autonomous navigation. The experimental evaluation was conducted on a small 20 m² outdoor test area and focused mainly on light debris such as dust and paper. The obstacle-detection system uses a single HC-SR04 ultrasonic sensor and is therefore limited in sensing field and environmental robustness. Solar charging performance also depends on solar irradiance and was not evaluated under different weather conditions. Further experiments involving larger areas, different debris types, varying surface conditions, longer operating periods, and multiple environmental conditions are required.

6. ACKNOWLEDGEMENT

The authors would like to express their sincere thanks to Dr. Mredhula. L, Head of the Department of Electronics and Communication Engineering, Nehru College of Engineering and Research Centre, Pampady, for her valuable guidance, continuous encouragement and unconditional support throughout this work. The authors would also like to thank all the faculty members and the institution for providing all the facilities and support required for the successful completion of this model.

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