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Improving Navigation of a Semi-Autonomous Solar Panel Cleaning Robot through Advanced Localization and Edge Detection

[1] Isuru Munasinghe*, [2] Vishva Vijenayake, [3] Dr. Peshala Jayasekara P.hD.

[1] [2] Student, Department of Electronic and Telecommunication Engineering, Faculty of Engineering, University of Moratuwa, Sri Lanka

[3] Department of Electronic and Telecommunication Engineering, Faculty of Engineering, University of Moratuwa, Sri Lanka

Orchid Id Number: [1] 0009-0005-0910-9795, [2] 0009-0001-0372-7710, [3] 0009-0003-6346-9754

Corresponding Author Email: [1] isuru.munasinghe1998@gmail.com, [2] oshadadias1998@gmail.com, [3] peshala@uom.lk

Abstract— ***Solar photovoltaic (PV) systems have become increasingly popular as a sustainable energy source due to the growing need for renewable energy on a global scale. However, the buildup of dust and dirt on solar panels frequently compromises the effectiveness of these systems. Existing cleaning methods often require manual labor, exhibit low efficiency, and are restricted to either a single cleaning method or operational mode. To address these issues, we designed and implemented a semi-autonomous solar panel cleaning robot capable of both dry and wet cleaning. The robot can autonomously navigate on solar panels with a tilt of up to 20° or be manually controlled using a mobile app, and it operates for approximately 75 minutes on a single charge. This study enhances key aspects of the robotic system, integrating advanced edge detection and transition mechanisms using both ultrasonic sensors and image processing techniques. We implemented a robust localization system based on bus-bar detection for precise navigation, upgraded the water supply mechanism and refined the orientation estimation algorithm.***

Keywords: Solar panel cleaning, semi-autonomous, edge detection, robot localization, drift cancellation.

I. INTRODUCTION

The growing demand for renewable energy has highlighted the crucial role of solar photovoltaic (PV) systems in sustainable energy. However, the efficiency of solar panels is often compromised by environmental factors, with accumulated dust and dirt potentially reducing their performance by 50-80% over time [1]-[3]. To address this challenge, our previous research work introduced a semi-autonomous robotic system (Fig. 1) for systematic solar panel cleaning that effectively integrates both dry and wet cleaning methods [4].

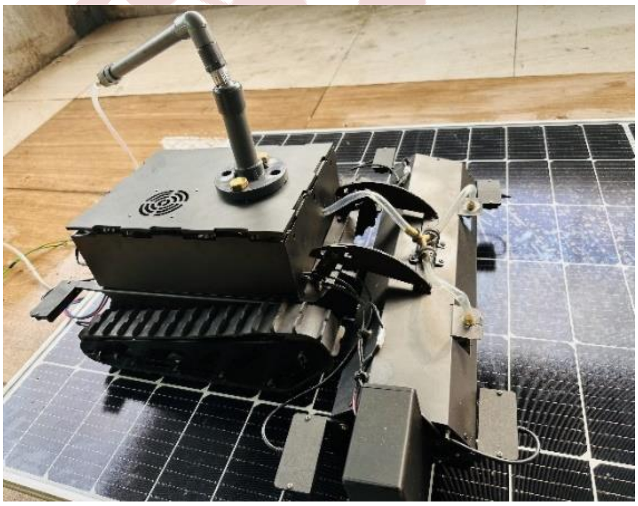

Figure 1. Designed solar panel cleaning robot

This robot leverages a mechanical roller brush as the cleaning mechanism and a tracked-wheel mechanism as the most suitable moving mechanism based on a comprehensive slip analysis study in ref. [5]. The system uses image processing algorithms for precise bus-bar detection, employs industrial ultrasonic sensors for reliable edge detection, and utilizes the Robot Operating System (ROS) for enhanced control and operational flexibility. Additionally, a user-friendly mobile app has been developed for manual control and real-time monitoring, allowing the robot to autonomously clean solar panels with a maximum tilt angle of 20°, accommodating a maximum gap of 50 mm between two panels, and covering approximately 17 m^2 within a 30-minute session.

Building upon this work, the current study aims to further enhance the robotic cleaning system by incorporating additional functionalities and improvements. Specifically, we introduce enhancements to address existing limitations and optimize system performance through the following contributions:

- We utilize inherited bus-bars along with image-processing techniques to localize the robot within the solar panel array.
- We propose an edge detection algorithm to identify the boundaries of the panel array and the gaps between two adjacent panels.
- We enhance the robot's orientation estimation algorithm by eliminating gyroscope drift, ensuring more accurate positioning and movement.

This paper is organized as follows: Section II presents a review of the relevant literature and related works. Section III outlines the system design and architecture of the robot and Section IV discusses the system enhancements made to improve the robot's performance. Section V details the experiments conducted and the results obtained. Finally, Section VI provides the conclusions of the study and explores potential directions for future research.

II. LITERATURE REVIEW

In this section, we discuss the existing robotic systems designed for cleaning solar panels. The system described in the paper [6], uses ultrasonic sensors for detecting the edges of solar panels. However, this study lacks a robust algorithm for differentiating between the termination of a solar panel array and the transitions between consecutive panels. The study referenced in [7] employs eight IR sensors facing downwards for edge detection. However, this approach encounters significant limitations due to the impact of direct sunlight on IR sensor readings as the varying light conditions in outdoor environments, such as rooftop solar installations, can interfere with the sensors' accuracy, leading to unreliable edge detection. The system described in [8] investigates robot localization using omni-directional wheel encoders, which can offer precise localization under ideal conditions. However, when used on solar panel arrays, this method is prone to errors due to the smooth surface of the photovoltaic (PV) panels, which can cause the robot to slip and result in inaccuracies in the encoder readings, leading to erroneous localization and navigation issues.

In ref. [9]-[11] explores the use of onboard water tanks for wet cleaning purposes. Although this method is effective for cleaning, it presents several practical challenges. Refilling the water tank can be difficult, particularly when the robot operates on rooftops. Moreover, when the water tank is completely filled, it significantly increases the robot's weight. This added weight applies excessive pressure on the PV panels and requires more power for operation, thereby reducing its efficiency and operational time. In fact, ref. [12] explores the use of a separate water line for the cleaning robot. Although this approach eliminates the need for an onboard water tank, it introduces complications, as the water line can affect the robot's navigation by snagging on obstacles or becoming entangled, which disrupts the robot's movement and may cause damage to both the robot and the solar panels if not managed by a specific mechanism.

III. SYSTEM DESIGN AND ARCHITECTURE

In this section, we provide an overview of the system design and control architecture, highlighting the key components and their interactions within the robotic system.

After considering several factors, the moving mechanism, cleaning mechanism, navigation mechanisms, controller boards, edge detection, and panel navigation were selected, as discussed in the previous paper [4]. The selected mechanisms and components are illustrated in Fig.2.

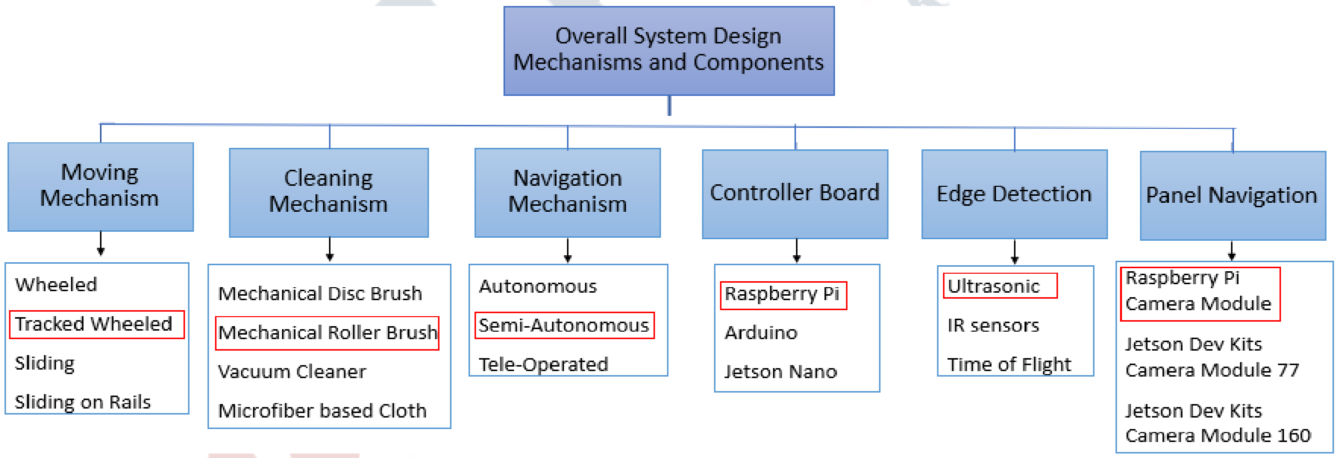

Figure 2. Overall system design mechanisms and components

The robot consists of two Raspberry Pi 3B+ boards placed in the top enclosure as in Fig.3. The primary Pi serves as the main control unit, managing operations and processing control signals from the mobile app, while the secondary Pi is dedicated to image-processing tasks using its integrated camera. Six industrial waterproof ultrasonic sensors are incorporated to enhance safety and facilitate smooth transitions between panels. The robot features a mechanical roller brush at the front for cleaning purposes, with a water pump activated for wet cleaning. Precise robot movement and brush activation are achieved through two dual-motor controllers. An Initial Measurement Unit (IMU) is integrated to accurately measure the robot's orientation and the tilt angle of the panel.

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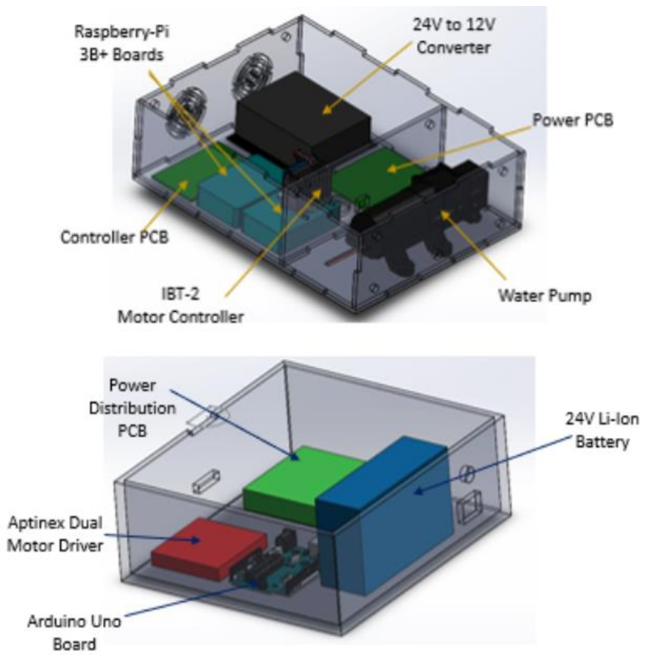

Figure 3. Component placement within top and bottom enclosures of the robot

The system employs Robot Operating System (ROS) platform for control purposes. Each component of the robot is designated as a node within ROS, following a publisher-subscriber model for the control architecture. The autonomous control algorithm implemented in this study remains consistent with the approach detailed in our previous work [4]. However, significant improvements have been made to the manual control system to enhance robot safety. We introduce an additional error-handling node, which was not present in the earlier version. This node plays a critical role in ensuring safety during manual operations. Specifically, if an ultrasonic sensor detects an edge directly ahead of the robot, any user attempts to drive the motors forward will be blocked. Instead, an error notification will be displayed on the mobile app, alerting the user and preventing potential accidents.

IV. SYSTEM ENHANCEMENTS

This section describes the various improvements made to the robotic system to enhance its overall performance.

A. Edge Detection and Transition Mechanism

The edge detection algorithm is implemented through the utilization of six ultrasonic sensors, positioned on both front and rear side of the robot. A detected distance exceeding 18cm is recognized by the robot as the termination of the solar panel array, prompting the robot to stop or reverse to avoid moving beyond the intended area. Distances of 18 cm or less are interpreted as gaps between consecutive solar panels, allowing the robot to transition smoothly between panels.

Fig. 4 illustrates the edge detection algorithm, where S1-S6 (represented by red dots) correspond to the ultrasonic sensors. In this algorithm, a value of 1 indicates the detection of an edge, while a value of 0 indicates no edge detected. To initiate the cleaning process, the robot must be placed at the corner of the solar panel array. The robot uses this algorithm to determine the first turn direction (either left or right) to be taken. Once the initial turn is determined, the robot can make subsequent turning decisions at the edges of the solar panel array based on the sensor readings.

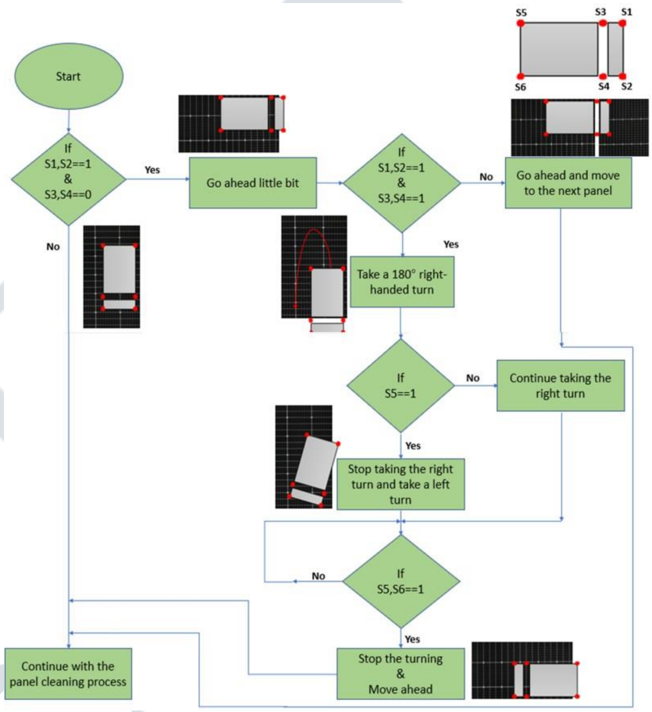

Figure 4. Edge-detection algorithm using ultrasonic sensors

In addition to the ultrasonic sensors, we employ image processing techniques to detect edges, enhancing the overall accuracy (Fig.5). The algorithm involves comparing the large contour area of the filtered image with the area of the bus bar. First, a filter is applied to the captured image to enhance edges and contours. Then, contours are identified in the filtered image, and the area of each contour is calculated. The estimated area of the bus bar is used as a reference. By comparing the contour areas with the estimated bus bar area, we determine the edges. If a contour area exceeds a certain threshold relative to the bus bar area, an edge is detected. This integrated approach ensures precise edge detection, improving the robot's safety.

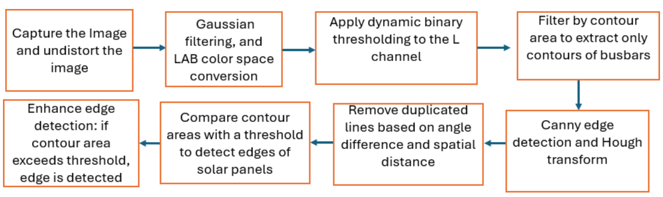

Figure 5. Image Processing algorithm for edge detection

B. Robot Localization using Bus-Bars

To localize the robot within the solar panel array, we leverage the inherent bus bars. We have implemented a bus-bar detection algorithm based on image processing. We use the outputs of the algorithm to count bus bars and detect edges as illustrated in Fig.4. The bus-bar counting algorithm mitigates accumulated errors associated with relative odometry measurements by employing an absolute measurement approach. This strategy utilizes bus-bars to track and estimate the distance traveled based on the standard dimensions of solar cells. The relevant data is then sent to the mobile application, enabling visualization of the robot's location within the PV panel array. The algorithm retrieves the current row and column numbers from a designated topic, identifies the specific cell being cleaned, and returns this information for precise localization. Additionally, the integration of this data into the mobile application allows for real-time monitoring.

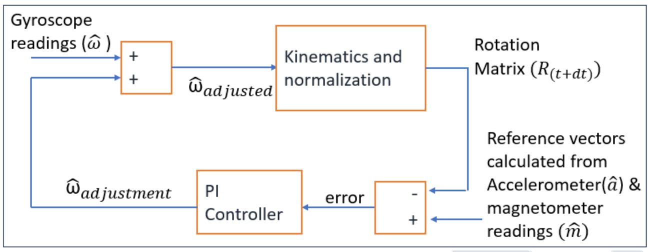

Figure 6. The block diagram of the PI Controller for the drift cancellation

C. Enhanced Orientation Estimation

To achieve accurate orientation estimation, we used an IMU (Inertial Measurement Unit) and implemented three parallel Kalman filters that utilize IMU readings.

Even though MEMS gyroscopes exhibit an inherent problem of continuous drift caused by internal attributes such as bias instability. To obtain accurate readings of the angular velocity, this drift must be corrected. To achieve this, other orientation references that do not drift are utilized, specifically the readings from the accelerometer and the magnetometer. The accelerometer reading provides the gravity vector and is used as a roll and pitch reference, while the magnetometer reading provides the horizontal course over the ground (COG) and serves as a yaw reference.

If we define the rotation matrix calculated from the gyroscope readings as, $R_B^E = (x_g^E, y_g^E, z_g^E)$, the projected x_g vector towards COG would be:

$$x_{gp}^E = (r_{11}, r_{21}, 0)^T$$

Here r_{xy} is donated as an entry of R_B^E. If the COG vector is,

$$COG^E = (x_{COG}, y_{COG}, 0)^T$$

The yaw error (e_{yaw}) can be calculated from the cross product of x_{gp} and COG^E.

$$e_{yaw} = x_{gp} \times COG^E = (0,0, r_{11}.y_{COG} - r_{21}.x_{COG})^T$$

If we transform it to body frame,

$$(e_{yaw})^B = (R_B^E)^T (e_{yaw})^E$$

$$(e_{yaw})^B = (r_{11}.y_{COG} - r_{21}.x_{COG})(r_{31}, r_{32}, r_{33})^T$$

The gravity vector from Gyroscope readings in body frame would be,

$$g_{gyro}^B = (R_B^E)^T (0,0,1)^T (-9.81)$$

$$g_{gyro}^B = -k(r_{31}, r_{32}, r_{33})^T, where, k = 9.81$$

If the gravity vector calculated from the accelerometer readings is g_{acc}^B, The roll and pitch error ($e_{roll,pitch}$) can be calculated from the cross product of g_{gyro}^B and g_{acc}^B as below.

$$e_{roll,pitch} = g_{gyro}^B \times g_{acc}^B$$

To cancel the drift, a PI controller is implemented such that e_{yaw} and $e_{roll,pitch}$ fed into the PI controller with fine tuned Kp and KI constants. The block diagram of the PI controller is shown in Fig.6. This controller effectively compensates for the gyroscopic drift by leveraging the stable and non-drifting orientation references from the accelerometer and magnetometer, resulting in improved accuracy in the estimation of the robot's orientation.

D. Improved Water Supply Mechanism

The initial consideration for integrating a water tank onto the robot was deemed unfavorable due to potential drawbacks. The added weight of a water tank would impede the robot's operation on the panels and exert high pressure, potentially damaging the PV panels. Additionally, a larger battery would be necessary to maintain the robot's operational duration, further reducing efficiency. To address these challenges, an alternative solution was proposed, which involved supplying water through a pressurized water line via a pump.

However, this approach also had its issues, as the water line could disrupt the robot's movement when traversing the panel. To solve this, a specialized mechanism was implemented to integrate the water supply system within the robot. By incorporating a ball joint as shown in Fig.7, the robot can achieve a complete rotational range of 360°, allowing the robot's motion to remain undisturbed by the water line.

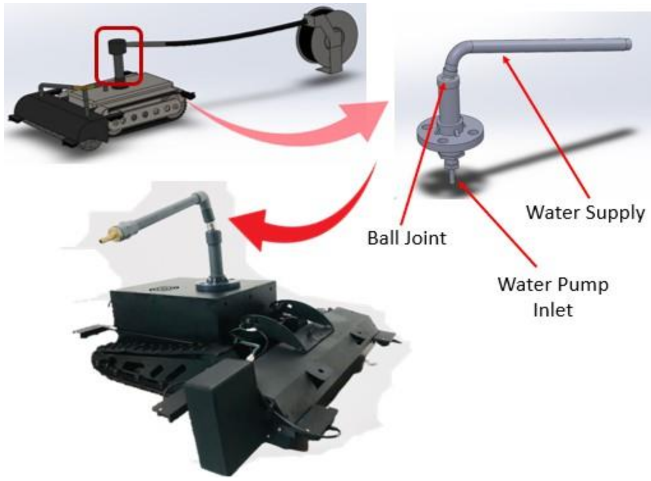

Figure 7. 360◦ rotating water supply mechanism

V. EXPERIMENTS AND RESULTS

In this section, we present the experiments conducted and their corresponding results.

A. Evaluation of robot localization within the PV panel array

The filtered image (Fig.8) is processed using the bus-bar counting algorithm (Fig.9) to determine the robot's location within the solar panel array. This localization is further refined using ultrasonic edge detection data. Consequently, the robot's position within the solar panel array, as well as its specific location within the individual panel, can be visualized in the mobile app (Fig.10).

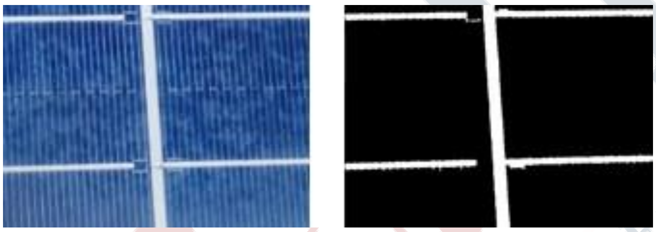

Figure 8. Filtered image of PV panel surface

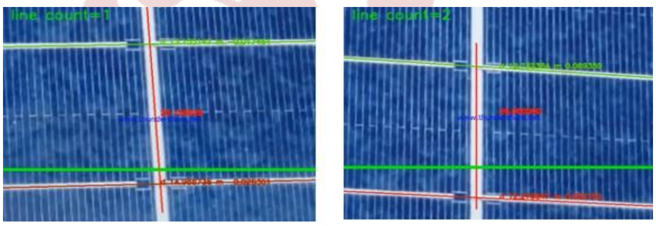

Figure 9. Robot localization using bus-bar counting algorithm

Figure 10. Visualization of robot location within the PV panel array on the mobile app

Table 1. Experimental results of edge detection algorithm under various lightning conditions

Test condition	Edge detection accuracy (%)
Ambient Light	98.90
Sunny	97.23
Cloudy	97.10

B. Evaluation of edge detection using image-processing

This evaluation, presented in Table I, includes a detailed analysis of the algorithm's effectiveness in identifying and differentiating edges between solar panels, as well as its accuracy in various lighting conditions.

VI. CONCLUSION

This paper presented significant enhancements to our semi- autonomous robotic system for solar panel cleaning, focusing on improving performance and addressing existing limitations. Key improvements include the implementation of image processing techniques and ultrasonic edge detection algorithm for localization and navigation within the solar panel array, enabling real-time visualization of the robot's location in the mobile app during the cleaning process. Furthermore, the elimination of gyroscope drift has improved the robot's orientation estimation, ensuring accurate positioning and movements.

Future work will focus on validating the cleanliness of solar panels through quantitative evaluation to ensure the effectiveness of the cleaning system.

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