International Journal of Innovative Research and Scientific Studies, 8(3) 2025, pages: 594-606

IJIRSS International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

The solar panel cleaning robot and real–time asset tracking record control via IOT system

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Abstract

This study presents the design and development of an IoT-enabled solar panel cleaning robot aimed at enhancing autonomous maintenance efficiency and enabling real-time asset tracking. The robot's movement and navigation were analyzed using differential kinematics and static analysis. A microcontroller-based control system with integrated IoT functionality allows remote operation via a web-based interface. Embedded GPS capabilities automatically log real-time location data (latitude and longitude) to Google Sheets for performance monitoring. The robot was tested on a solar panel array measuring 4.8 × 8.72 meters (81.86 m²), completing the cleaning process in 15 minutes. Compass accuracy was evaluated using the Mean Absolute Percentage Error (MAPE) across three movement patterns: Vertical Spiral (168.19), Horizontal (11.31), and Cycle Spiral (44.78), highlighting variations in directional performance. The integration of IoT and GPS with autonomous control provides a practical, scalable solution for efficient solar panel maintenance and location tracking. The robot demonstrates strong potential for real-world application in large-scale solar energy systems. Future enhancements will focus on improving precision navigation using sensor fusion techniques, such as Kalman and Butterworth filters, to increase the accuracy and stability of GPS and compass data under diverse environmental conditions.

Keywords: Compass and GPS tracking, dust accumulation, Internet of Things, latitude and longitude, solar panel cleaning robot.

DOI: 10.53894/ijirss.v8i3.6578
Funding: This study received no specific financial support.
History: Received: 19 March 2025 / **Revised:** 22 April 2025 / **Accepted:** 24 April 2025 / **Published:** 29 April 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Acknowledgment: Deep gratitude goes to Rajamangala University of Technology Thanyaburi for the support in facilities. We would also express our deepest gratitude to the Rajamangala University of Technology Thanyaburi (RMUTT) for the facilities that have been provided to support this research.
Publisher: Innovative Research Publishing

1. Introduction

A study throughout history has shown that natural resources play a pivotal role in establishing the global electric power system. Electric production has traditionally relied on combustion methods for power generation; this approach emits greenhouse gases, pollutes the environment, exacerbates global warming, and heightens the risk of catastrophic events [1]. Solar energy, as a renewable energy source, is essential for addressing the growing global demand for electricity [2]. Experts have been focused on improving solar panel efficiency, maximizing energy from the sun, and advancing control of electrical power. Importantly, the solar panel is a component that absorbs sunlight to generate electricity [3]. It is typically installed on a roof, and if there is dust on the surface, the electric power performance will be reduced.

Generally, if solar panels are not cleaned regularly, their performance can decline by 40-50% [4-7]. The frequency of cleaning is crucial to address dust accumulation, a major factor that reduces efficiency by blocking sunlight [8, 9]. The IoT-controlled Solar Cleaning Robot offers an innovative solution to improve energy production and system performance [10].

Several studies in control systems have been conducted on the DC motors to contribute the horizontal movement of the robot on the solar panels' surface with attached to the solar panel [11] and development of a mobile robot system for monitoring and cleaning process [12] the main frame attached to cope with these problems that difficult on movement to other Solar Panels. A Semi-automatic has designed and implement with design of Automatic Cleaning System on Solar (IOT) and wireless networking, the multi dataset was compiled utilization a variety camera and sensors to detect static and moving objects to serve as the foundation for the development of automated cleaning, the development to a four wheel and IOT control system at a relate high cost to cleaning process [13-17]. Furthermore, numerous studies have been conducted to optimize the Solar cleaning robot's mechanical performance, installed control systems and software, enabling it to operate and be controlled by a distance. These comprehensive studies are focused on powerful two-wheeled.

This study presents a novel low-cost solar cleaning robot using Arduino ESP8266, enabling flexible movement and enhanced IoT integration [18-25]. Controlled via a URL platform, this is the first remote-control system for operating such robots. Key contributions include the design and implementation of mechanics, electronics, and software, integrated with an IoT system. This platform allows the solar cleaning robot's IoT control system to move remotely via smartphones using a URL, cleaning solar panels without heating up or posing risks to workers. The system connects to the internet via Wi-Fi, with unlimited range. The second contribution is real-time GPS and compass data logging to Google Sheets [26-28]. An effective pursuit controller algorithm facilitates autonomous movement from one coordinate to another by utilizing GPS data for accurate positioning. As part of a preliminary study, we collected data from GPS and compass sensors during field tests [29-34]. The collected data was subjected to filtering to address issues of noise and instability. In this context, compared the performance of Kalman and Butterworth low-pass filters to identify the most suitable option for improving the accuracy of the sensor data.

The proposed system integrates automation by combining Internet of Things (IoT) and Global Positioning System (GPS) analysis, offering flexibility in robot operations. The control system allows for remote operation, significantly improving efficiency and convenience in system management.

2. Materials and Methods

2.1. Measurement Methodology

MAPE (Mean Absolute Percentage Error). MAPE (Mean Absolute Percentage Error) is a relative measure that scales MAD to a percentage. By using absolute values to prevent of errors and enables comparison of estimate accuracy of time series models [35, 36].

$$M = \frac{1}{n}\sum_{i=0}^{n}\left|\frac{A_t - F_t}{A_t}\right|$$

where A_t represents the actual value and F_t the forecasted value. The differences are divided by the actual value of A_t. The absolute ratio value is summed across all forecasted points then divided by the number of fixed points n.

MAD (Mean Absolute Deviation). It measures the average absolute distance between each data point and the mean from the data set, similar to standard deviation. Other statistical measures are also abbreviated as "MAD". [37] The average absolute deviation is a statistic that measures the variability of quantitative data.

$$MAD = \frac{\sum|x_i - \overline{x}|}{n}$$

For the unchanged of data set X_1, X_2, X_3 , to define from a median of the exact deviations from median $\overline{X}$ = median (X). Specifically, this is median of the valid values of deviations from the median.

$$MAD = median(|X_i - \overline{X}|)$$

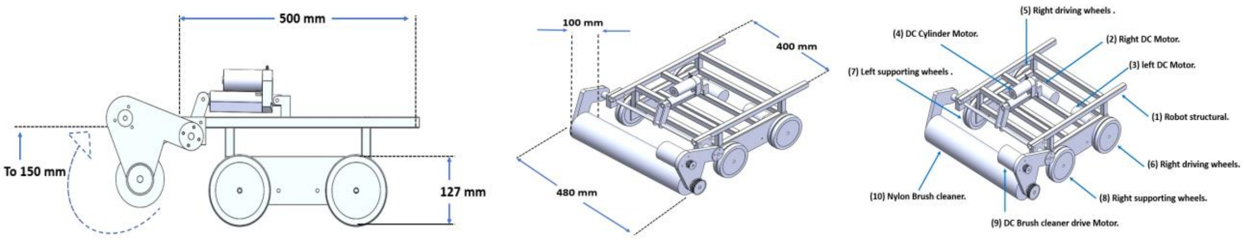
MSD (Mean-square displacement the variance-related diameter (VRD), twice the square root of the MSD. This appears in the Debye-Waller factor and Langevin equation; the particle's probability density function (PDF) is derived from the diffusion equation, which Einstein first used to describe Brownian motion. Langevin introduced an alternative Brownian motion model [38, 39].

$$MSD \equiv \langle |X\,(t)\; - \;X_0|^2 \rangle \; = \frac{1}{N} \sum_{i=1}^{N} \left| X^{(i)}(t)\; - \;X^{(i)}\,(0) \right|^2$$

While N is the number of data averaged, the $X^{(i)}(0) = X_0^{(i)}$, this reference of the i-th, the $X^{(i)}(t)$ represents the position of the i-th of at time (t).

2.2. Hardware Robot Design

The foundation of the IoT Solar Cleaning Robot is constructed from stainless steel and has dimensions of 500 millimeters in length and 400 millimeters in width. It features 127 mm wheels, two driving motors, and is supported by two wheels as Figure 1 (a). The brush cleaner has referred to Nylon material measures 480 millimeters as Figure 1 (b) and able raised up to a maximum of 150 millimeters from the surface using a Cylinder Motor [6] with high-speed DC motor for rotary brush control, the Nylon bristles that are 25 millimeters long with a 0.2-millimeter site, hardware Robot design as Figure 1 (c).



(a) (b) (c)

Figure 1.
The Solar Panels Cleaning Robot and GPS automatic tracking record control via IOT.

2.3. Controller Hardware Robot design

The ESP32 is used in the controller system, the ESP32 connects to other devices to enable Wi-Fi functionality. The IBT-2 (BTS7960) is a low-power motor driver module (PWM at 25kHz with active freewheeling). It operates 12 direct current voltage (VDC) with a maximum capacity of 43 amperes with various control overvoltage. The interface accepts sensor data and transfers it to the attached device for the Robot protection driver during moving process. The Solar Panels Cleaning Robot has moving control. The ESP8266 is Wi-Fi module for Global Positioning System (GPS) which communicates with Anto and Firebase program via Internet of Things (IoT) and utilizes a Global Positioning.

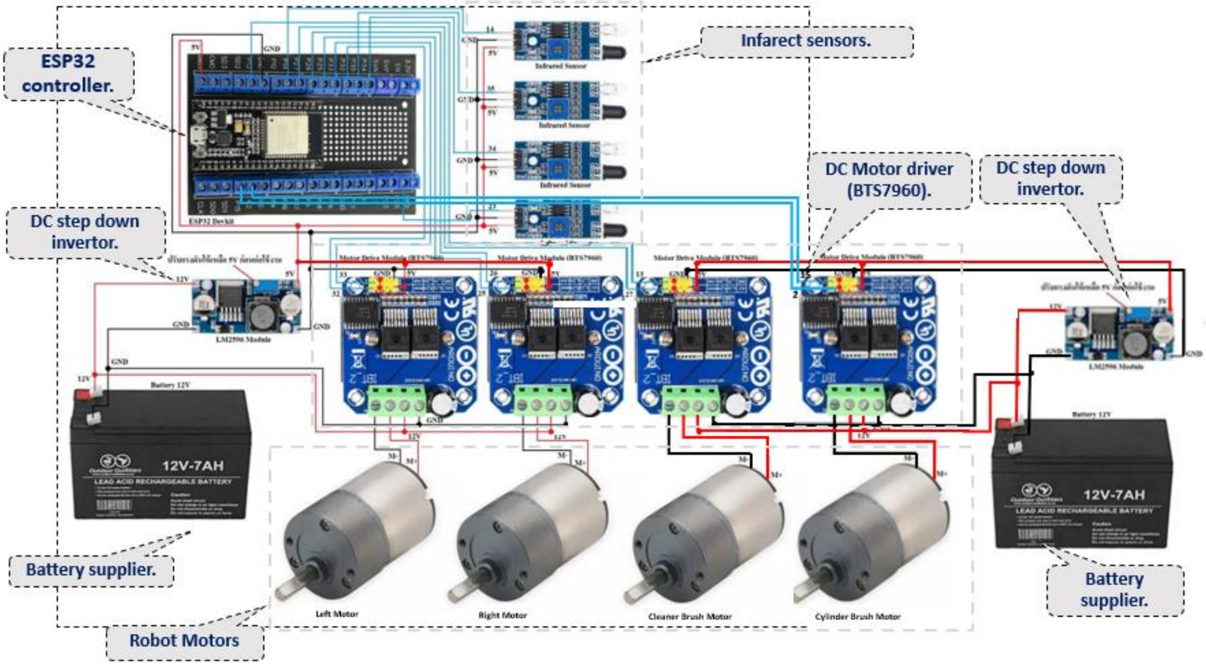


Figure 2.
The Solar Cleaning Robot circuit control diagram.

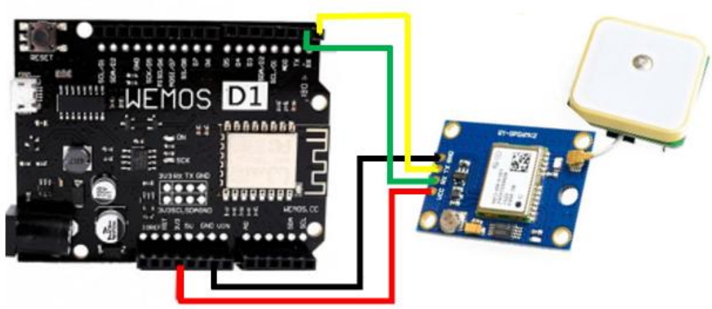


Figure 3.
The Solar Cleaning Robot ESP8266 circuit control diagram.

The Solar Cleaning Robot has positioned at the starting test location, controlled via IoT on moving process by following the research array panel settings until the processing is completed. The Global Positioning System (GPS) automatically recorded the robot's movement and marked the completion of the test at the designated location as Figure 4.

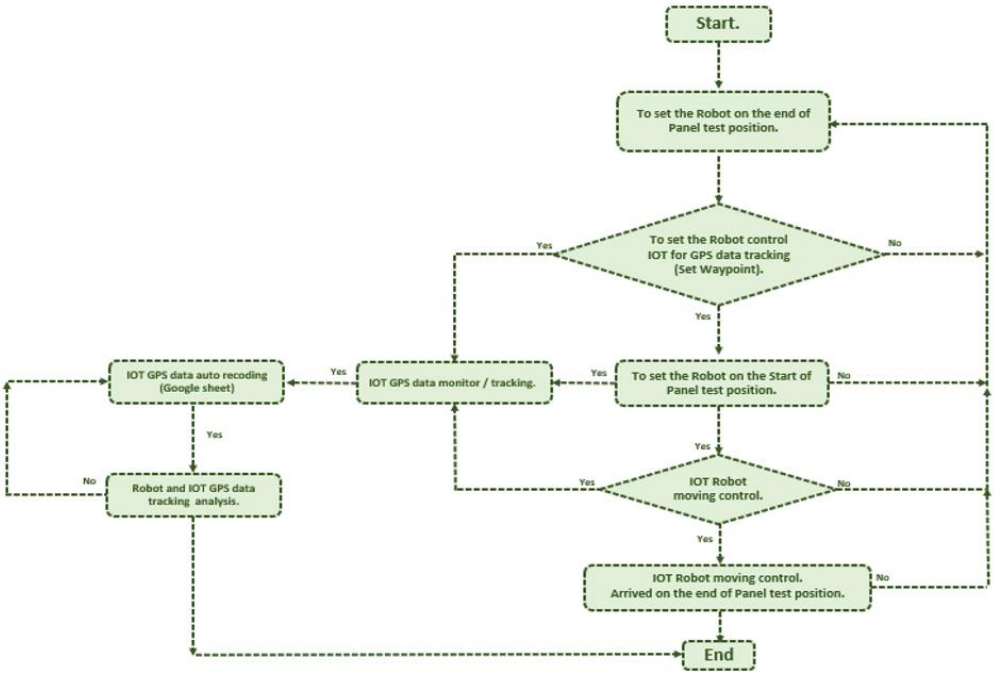


Figure 4.
The Flow Chart of Solar Cleaning Robot demonstrates the working process.

2.4. Global Positioning System (GPS) and Compass

Every location on Earth is defined by geographic coordinates, consisting of latitude and longitude (Lat/Long). Latitude and longitude are represented by numerical values on a grid made up of horizontal and vertical lines. Latitude lines are imaginary horizontal lines around the Earth, with the Equator as the central line, dividing the Earth into the Northern and Southern Hemispheres at 0 degrees. Longitude lines, or meridians, are vertical slices through the Earth, with the Prime Meridian at 0 degrees, measuring locations east and west. This is 180 degrees of longitude east and 180 degrees of longitude west of the meridian, as shown in Figure 5.

The compass is a device used for determining directions. A magnetic needle always aligns with magnetic north. In navigation, a magnetic compass is used to determine direction on the Earth's surface by aligning itself with the Earth's magnetic field.

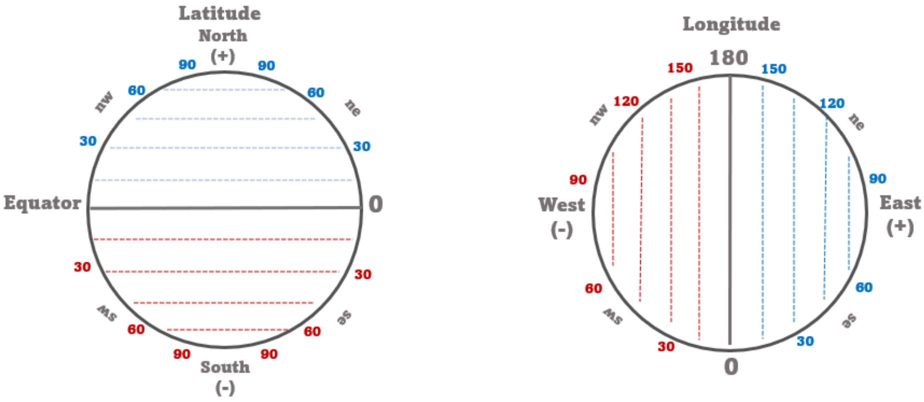


Figure 5.
Latitude and Longitude reference line.

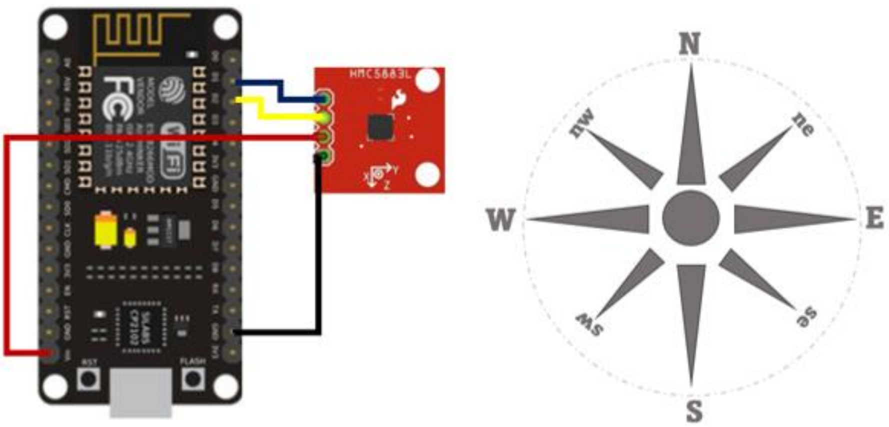


Figure 6.
The Solar Cleaning Robot ESP8266 with magnetic compass circuit diagram.

2.5. Experiment and Evaluation

To a waypoint experiment design was conducted using the solar panel array measuring 4.8 meters by 8.72 meters, totaling 81.86 square meters, as Figure 7. The system generates approximately 620 watts per 1 solar panel, total energy performance of around 9,920 watts (620 watts × 16 solar panels). The Spiral movement is designed as steps, 1) Firstly by vertical Spiral movement consisting of 158 points as Figure 8 (a), 2) Secondly by horizontal Spiral movement consisting of 112 points as Figure 8 (b), and 3) Lastly by cycle spiral movement consisting of 107 points as Figure 8 (c).

Figure 7.
Solar panel arrays.

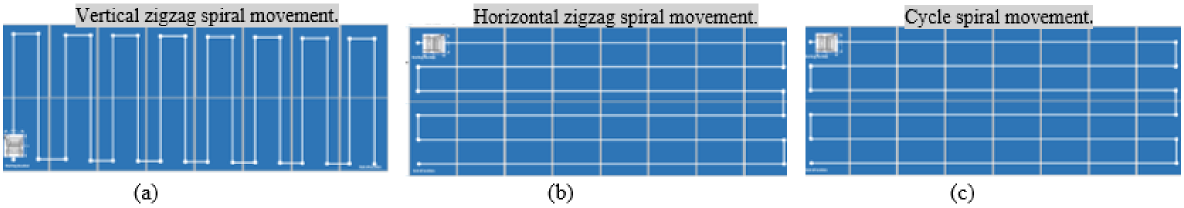


Figure 8.
Spiral movement design.

3. Results and Discussion

3.1. Hardware Implementation

The ESP32 controller receives various input signals, including a URL link, as shown in Figure 9. It is responsible for managing the movement and cleaning processes of the solar panel cleaning robot. The hardware setup includes 1) Robot structural, 2) Right side DC Motor, 3) Left side DC Motor, 4) DC Cylinder Motor, 5) Right side driving wheels, 6) Left side driving wheels, 7) Left side wheels, 8) Right side wheels, 9) DC Brush cleaning driving Motor and 10) the brush cleaner is made of Nylon material as Figure 10.

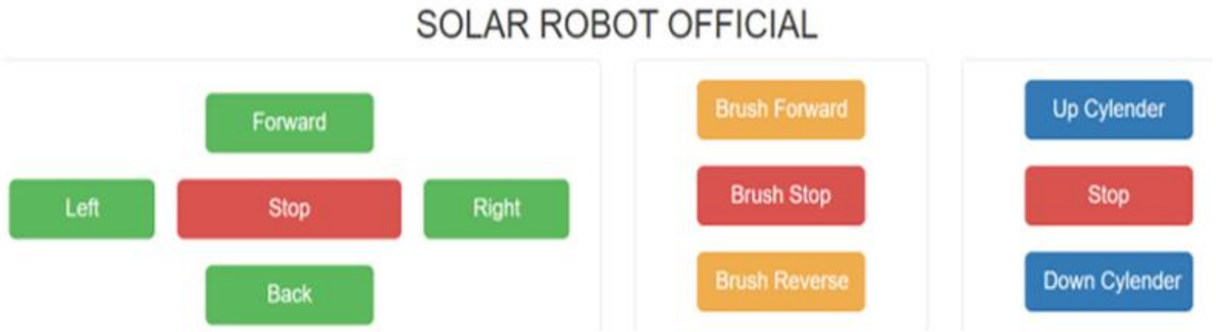


Figure 9.
The URL IOT Robot control.

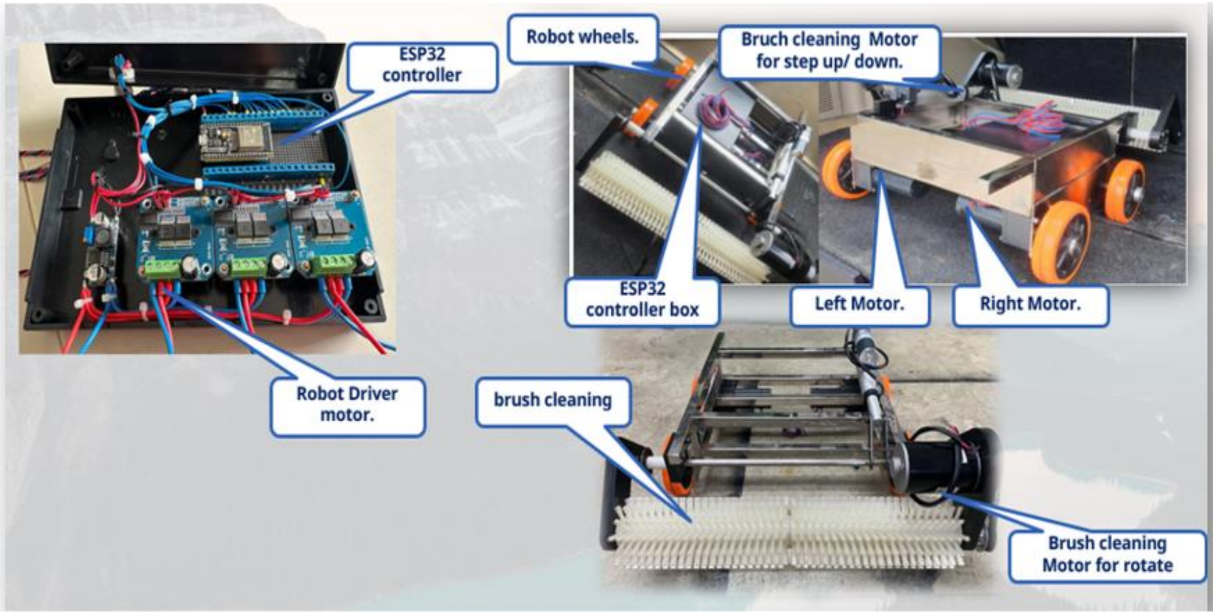


Figure 10.
Solar Cleaning Robot Structural.

3.2. Internet of Things

The programming language, used with HTML, CSS, and JavaScript, enables dynamic web behavior. It supports user input validation, page updates, and interactivity. Combined with Anto.io for communication and server management, configuration is crucial for the research methodology, as Figure 11.

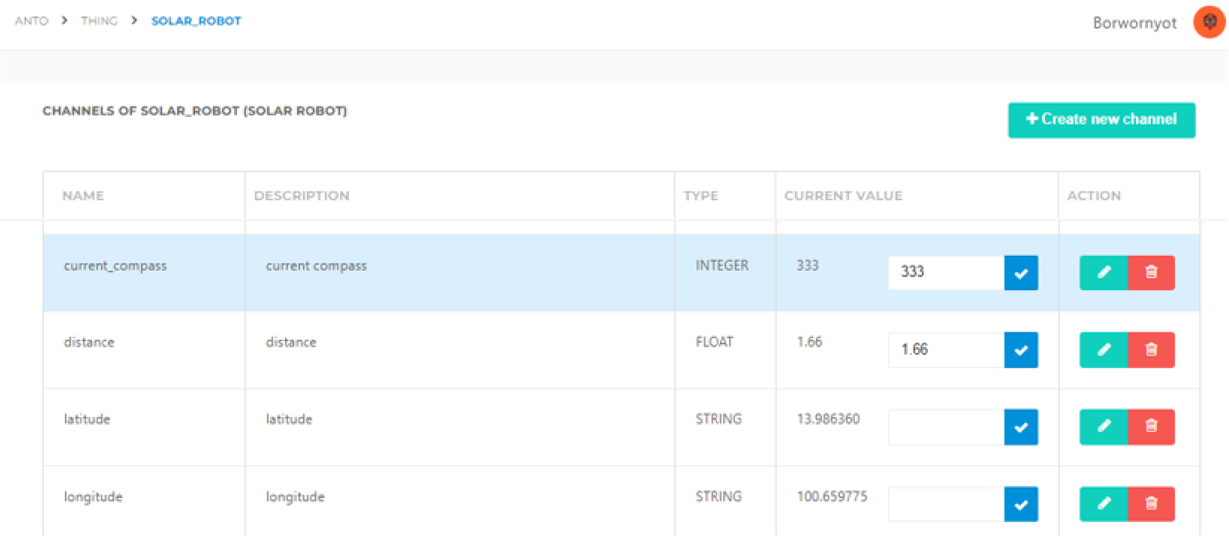


Figure 11.
IOT Anto Platform.

The GPS status is automatically recorded on a Google Sheets site, capturing the Latitude, Longitude, Target Latitude, Target Longitude, Current Compass, Target Compass, and Distance to Target as Figure 12. The IoT data is similarly automatically recorded in Google Sheets format, illustrated as Figure 13.

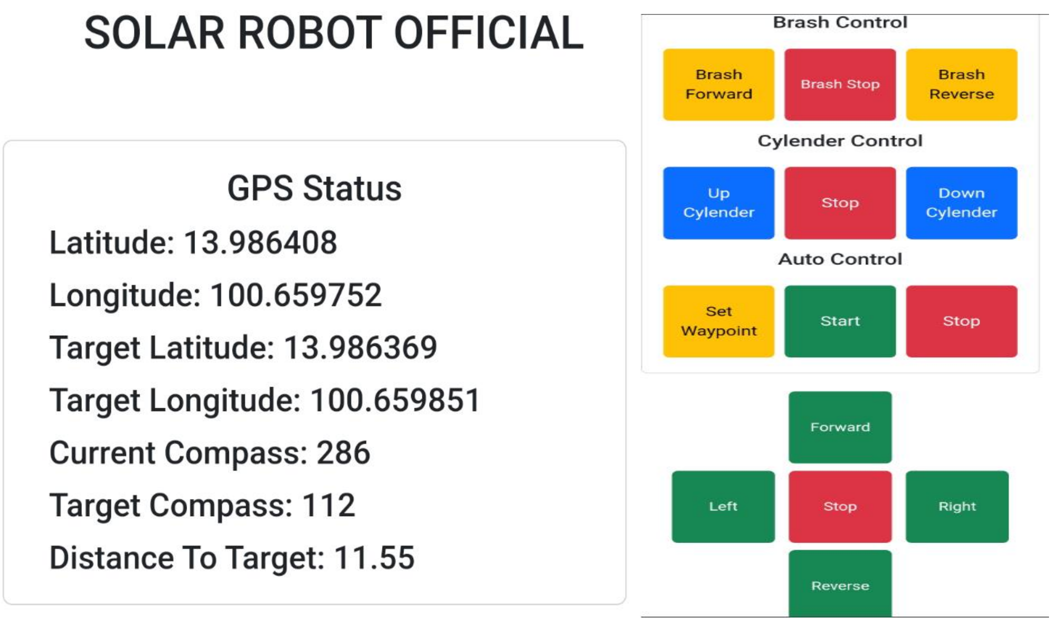


Figure 12.
GPS status monitoring and IOT Robot control panel.

Date	Time	Latitude	Longtitude	Target Latiture	Target Longtitude	Distance (meter)	Compass (C degree)	Target Compasss (C Degree)
11/7/2024	15:41:24	13.986490	100.659790	13.986478	100.659813	2.83	27	119
11/7/2024	15:41:33	13.986490	100.659790	13.986478	100.659813	2.83	27	119
11/7/2024	15:41:52	13.986490	130.659790	13.986478	120.659813	20.83	27	119
12/7/2024	7:08:18	13.986490	100.659790	13.986478	100.659813	2.83	27	119
13/7/2024	13:18:37	13.986490	100.659790	13.986478	100.659813	2.83	27	119
13/7/2024	13:27:17	13.990000	100.660000	13.990000	100.660000	8.51	20	337
13/7/2024	13:36:16	13.990000	100.660000	13.990000	100.660000	6.61	21	330
13/7/2024	13:36:19	13.990000	100.660000	13.990000	100.660000	6.15	19	327
13/7/2024	13:36:24	13.990000	100.660000	13.990000	100.660000	5.89	22	325
13/7/2024	13:36:26	13.990000	100.660000	13.990000	100.660000	5.99	24	316
13/7/2024	13:36:29	13.990000	100.660000	13.990000	100.660000	5.69	14	313
14/7/2024	17:16:00	13.990000	100.660000	13.990000	100.660000	5.69	352	313
14/7/2024	17:16:03	13.990000	100.660000	13.990000	100.660000	5.69	281	313
14/7/2024	17:16:06	13.990000	100.660000	13.990000	100.660000	6.87	285	314
14/7/2024	17:16:08	13.990000	100.660000	13.990000	100.660000	6.87	285	314
14/7/2024	17:16:11	13.990000	100.660000	13.990000	100.660000	8.75	187	318
14/7/2024	17:16:13	13.990000	100.660000	13.990000	100.660000	8.75	190	318
14/7/2024	17:16:16	13.990000	100.660000	13.990000	100.660000	8.06	185	322
14/7/2024	17:16:18	13.990000	100.660000	13.990000	100.660000	8.06	188	322
14/7/2024	17:16:21	13.990000	100.660000	13.990000	100.660000	7.05	199	324

Figure 13.
Google sheet GPS status recording format.

3.3. Research Experiment Result

Firstly, by vertical Spiral movement consisting of 158 points, the research designed has involves automatic tracking GPS parameters which is position 1 (A) for the starting point and position 158 (B) for the end of experiment location, covering a total of 8 cycles as Figure 14.

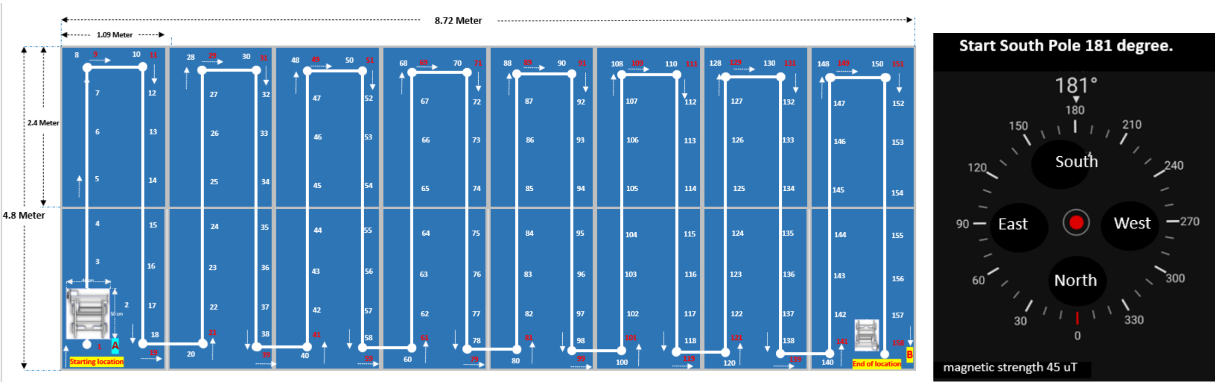


Figure 14.
Vertical Spiral movement automatic GPS parameters pattern.

The Solar Cleaning Robot of vertical Spiral movement with automatic GPS parameters recording. This methodology captures real-time GPS recording data auto recording into a Google Sheet for analysis. The display latitude and longitude from the starting at position (A) of compass direction is 181 degrees of South Pole and following the vertical spiral movement pattern at starting position (A) to completely at position (B), the latitude is recorded 13.98636 and longitude 100.659874 and the latitude is recorded 13.986454 and longitude 100.659798 of the end location (B) as Figure 15.

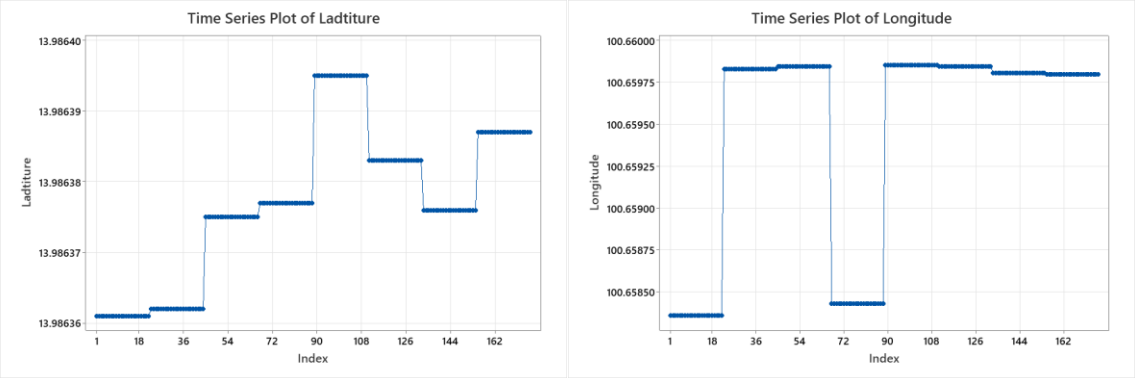


Figure 15.
Latitude and Longitude data analysis by Vertical Spiral movement.

The compass analysis provides detailed movement data, which references the initial starting direction with the compass at 181 degrees (South Pole) at position (A) until the completion of the process at position (B). The robot was moved toward the target and then automatically performed GPS data recording, which is the actual compass and target compass reference for the robot's performance accuracy moving analysis. The MAPE (Mean Absolute Percentage Error), MAD (Mean Absolute Deviation), and Mean-square displacement (MSD) were the measurement methodologies in this research. The actual compass accuracy measurement showed 256.3 for MAPE (Mean Absolute Percentage Error) analysis, 95.2 for MAD (Mean Absolute Deviation), and 10974.4 for Mean-square displacement (MSD). The target compass accuracy measurement showed 168.19 for MAPE (Mean Absolute Percentage Error) analysis, 61.87 for MAD (Mean Absolute Deviation), and 6849 for Mean-square displacement (MSD) as Figure 16.

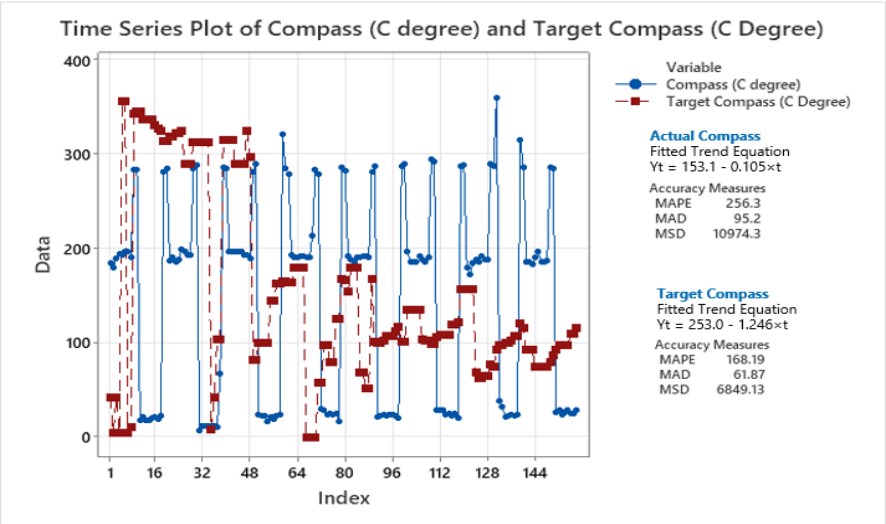


Figure 16.
Compass history recording by Vertical Spiral movement.

Secondly, by horizontal Spiral movement with consisting of 112 points, the research designed has involves automatic tracking GPS parameters, which is position 1 (A) for the starting point and position 112 (B) for the end of experiment location, covering a total of 3 cycles as Figure 17.

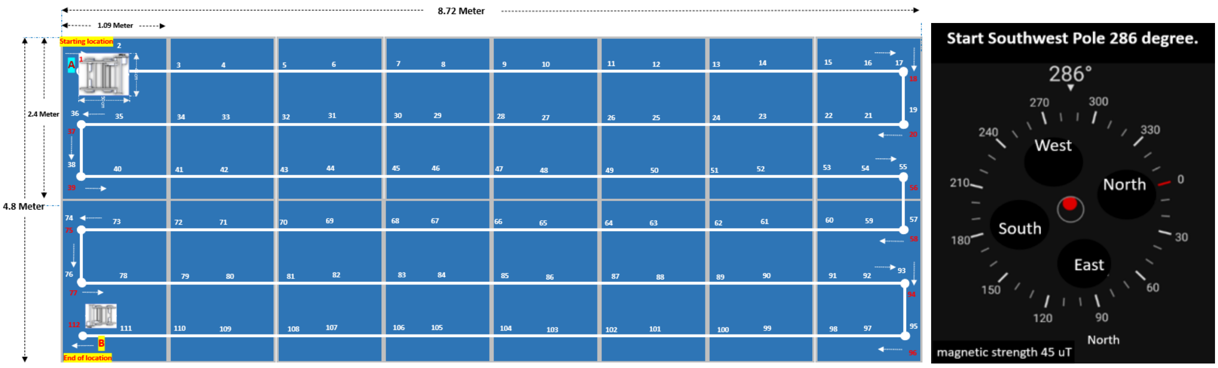


Figure 17.
Horizontal Spiral movement automatic GPS parameters pattern.

The Solar Robot of Horizontal Spiral movement with automatic GPS parameters recording. This methodology captures real-time GPS recording data auto recording into a Google Sheet for analysis. The latitude and longitude from the starting position (A) of compass direction is 286 degrees of North Pole and following the horizontal spiral movement pattern from starting position (A) to completely at position (B), the latitude is recorded as 13.986411 and longitude as 100.659821, and the latitude is recorded as 13.986346 and longitude as 100.65813 of the end location (B) as Figure 18.

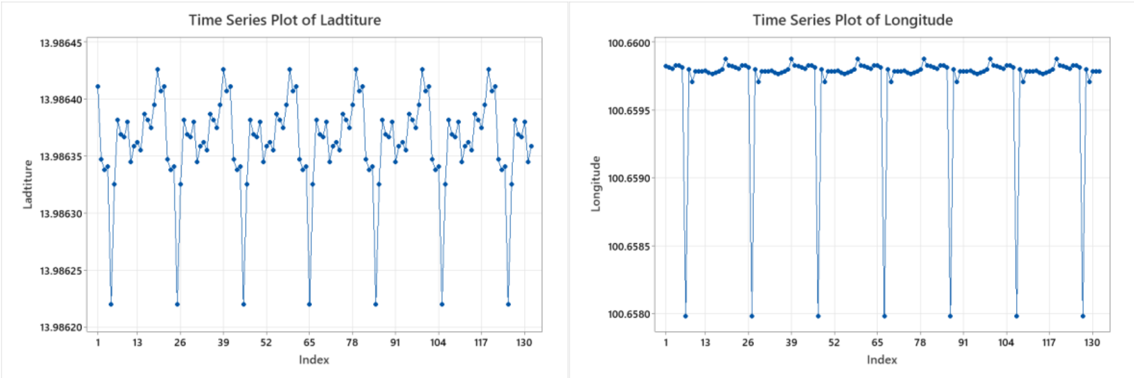


Figure 18.
Latitude and Longitude data analysis by Horizontal Spiral movement.

The compass analysis provides detailed movement data, which the initial starting direction of reference with the compass is 25 degrees (North Pole) at position (A) until the completed process at position (B). The robot was moved toward and then automatically performed GPS data recording, which is the actual compass and target compass reference for robot performance accuracy moving analysis. The MAPE (Mean Absolute Percentage Error), MAD (Mean Absolute Deviation), and Mean-square displacement (MSD) were the measurement methodologies in this research. The actual compass accuracy measurement showed 89.81 for MAPE (Mean Absolute Percentage Error) analysis, 76.85 for MAD (Mean Absolute Deviation), and 8138 for Mean-square displacement (MSD). The target compass accuracy measurement showed 11.312 for MAPE (Mean Absolute Percentage Error) analysis, 15.596 for MAD (Mean Absolute Deviation), and 392.433 for the Mean-square displacement (MSD) as Figure 19.

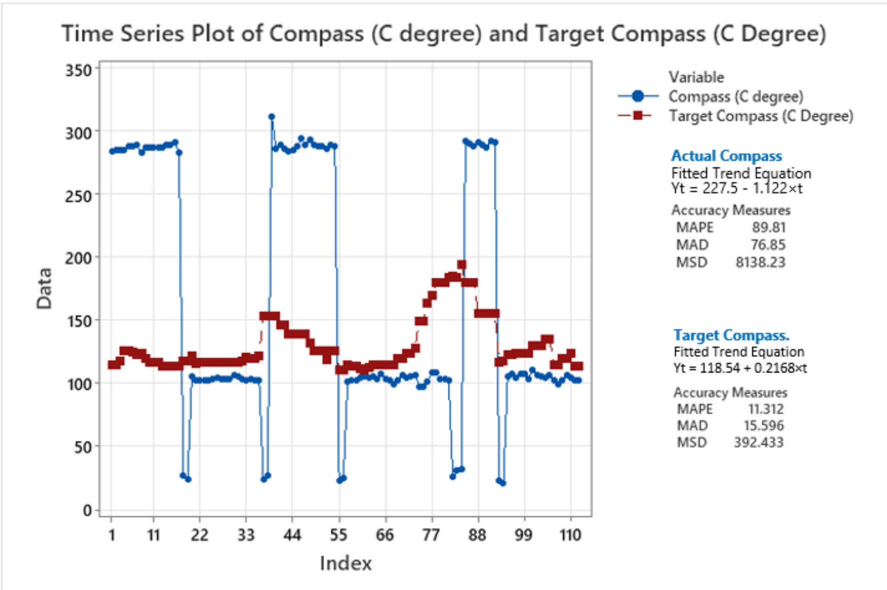


Figure 19.
Compass history recording by Horizontal Spiral movement.

Lastly, by cycle spiral movement consisting of 107 points, the research designed has involves automatic tracking GPS parameters which is position 1 (A) for the starting point and position 107 (B) for the end of the experiment location, covering a total of 3 cycles as Figure 20.

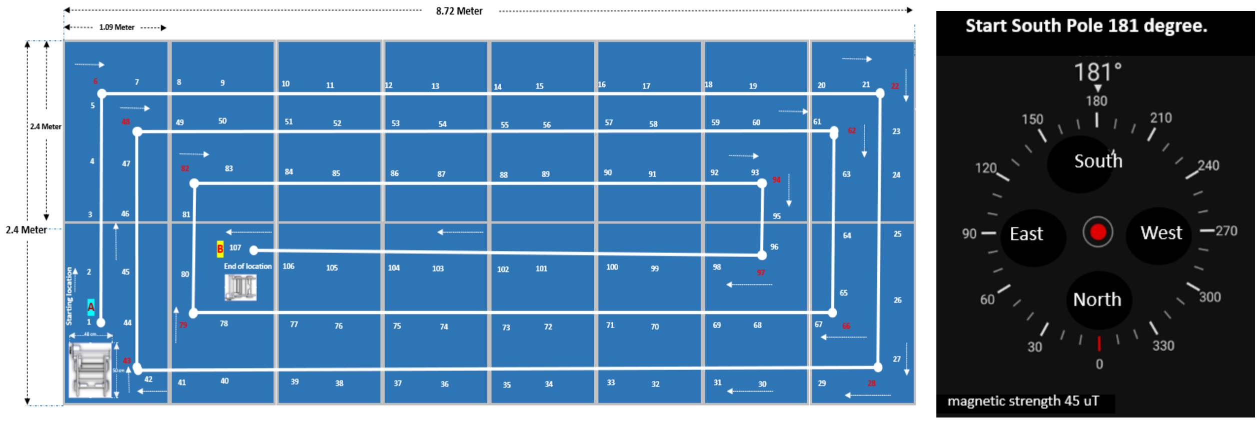


Figure 20.
Cycle spiral movement automatic GPS parameters pattern.

The Solar Cleaning Robot Control via IoT of Cycle Spiral movement with automatic GPS parameters recording. This methodology captures real-time GPS recording data auto recording into a Google Sheet for analysis. The display latitude and longitude from the starting at position (A) of compass direction is 181 degrees of South Pole and following the horizontal spiral movement pattern at starting position (A) to completely at position (B), the latitude is recorded 13.986393 and longitude 100.659874 and the latitude is recorded 13.986189 and longitude 100.659815 of the end location (B) as Figure 21.

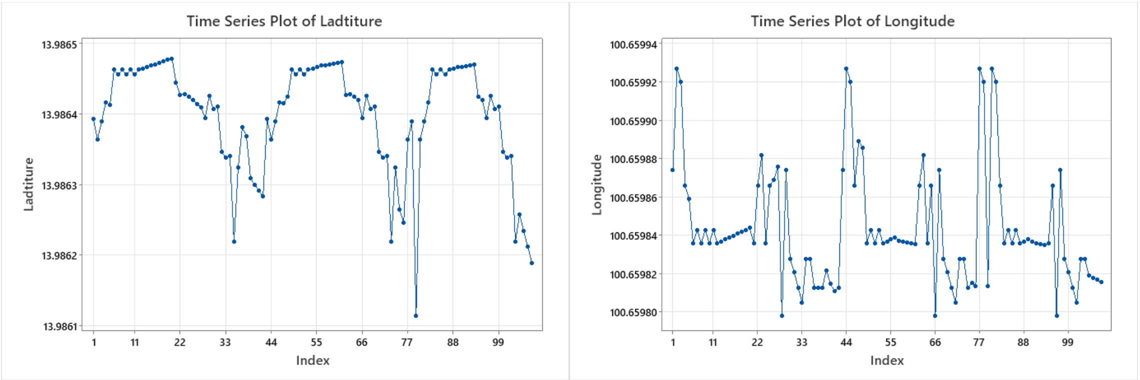


Figure 21.
Ladtiture and Longitude data analysis by Cycle spiral movement.

The compass analysis provides detailed movement data, which the initial starting direction of reference with compass 181 degrees (South Pole) at position (A) until the completed process at position (B). The Robot was moved toward and then automatically performed GPS data recording, which is the actual compass and target compass have references for Robot performance accuracy moving analysis. The MAPE (Mean Absolute Percentage Error), MAD (Mean Absolute Deviation), and Mean-square displacement (MSD) were the measurement methodologies in this research. The actual compass accuracy measurement showed 173.0 of MAPE (Mean Absolute Percentage Error) analysis, 112.3 of MAD (Mean Absolute Deviation), and 14722.6 of Mean-square displacement (MSD). The target compass accuracy measurement showed 44.78 of MAPE (Mean Absolute Percentage Error) analysis, 72.73 of MAD (Mean Absolute Deviation), and 7221.44 of the Mean-square displacement (MSD) as Figure 22.

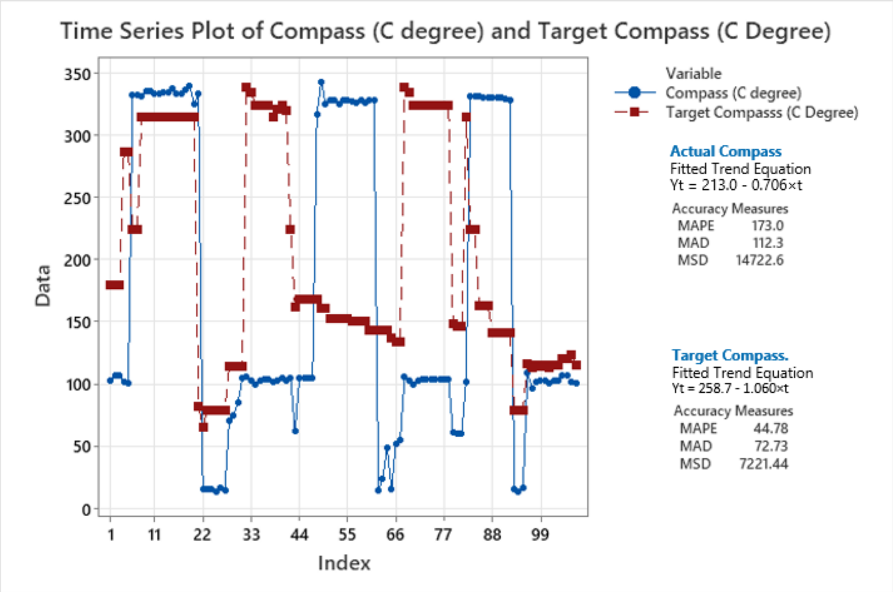


Figure 22.
Compass history recording by Cycle spiral movement.

4. Conclusion

In this research, a solar panel cleaning robot was successfully designed and tested, incorporating GPS tracking and automatic data recording via IoT technology. The robot integrates various electronic components and utilizes IoT for efficient control. To evaluate the robot's movement efficiency on standard residential solar panels, measuring 4.8 meters by 8.72 meters (81.86 square meters), the study employed three measurement methodologies: MAPE (Mean Absolute Percentage Error), MAD (Mean Absolute Deviation), and Mean-Square Displacement (MSD). The findings showed that the robot's GPS-guided movement was effective, with data collected across three different movement methodologies. The analysis of the GPS system data revealed the following accuracy for each methodology:

Vertical Spiral Methodology: MAPE = 256.3, MAD = 95.2, MSD = 10,974.4.

Horizontal Spiral Methodology: MAPE = 89.81, MAD = 76.85, MSD = 8,138.

Cycle Spiral Methodology: MAPE = 173.0, MAD = 112.3, MSD = 14,722.6.

On average, the robot completed the cleaning task in 14 minutes. These results provide valuable insights into the robot's autonomous movement performance and accuracy, highlighting its potential for effective operation in solar panel cleaning applications.

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