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Design of an IoT-Based Smart Pole for Detecting Manipulation of Plantation Boundary Markers

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Abstract - *Boundary markers are vulnerable to displacement and manipulation, while conventional inspection methods are unable to provide real-time monitoring. This study proposes an Internet of Things (IoT)-based Smart Pole system integrating a uBlox NEO-M8N GNSS module, HMC5883L magnetometer, LoRa EBYTE E32 communication, SIM7600G-H cellular gateway, and a solar-powered subsystem for autonomous boundary marker monitoring. System performance was evaluated through sensor accuracy, communication reliability, and integrated testing. Results showed that the GPS module achieved an average positioning error of 1.60 m (89.33% accuracy), while the HMC5883L achieved an average orientation error of 3.11%, with a maximum MAE of 1.70° and RMSE of 2.05°. The LoRa EBYTE E32 achieved an average PDR of 97.75% with 2.25% packet loss, whereas the SIM7600G-H gateway achieved a 97.0% success rate with 3.0% communication error. The solar subsystem, consisting of a 30 W photovoltaic panel and a 12 V 7.5 Ah SLA battery, provided stable autonomous operation. Integrated testing confirmed reliable detection of displacement and orientation changes, real-time dashboard visualization, and Telegram alert delivery. These results demonstrate that the proposed Smart Pole is a reliable and energy-autonomous solution for real-time plantation boundary marker monitoring.*

Keywords: *IoT, Smart pole, Boundary marker monitoring, GNSS, LoRa, HMC5883L*

I. Introduction

In the field of land surveying, boundary markers are widely used to define the boundaries of plantations, agricultural land, and forest areas. However, these markers are vulnerable to displacement, theft, and intentional manipulation, which may lead to boundary disputes and economic losses. Monitoring is commonly performed through periodic field inspections, a process that is time-consuming, labor-intensive, and ineffective for detecting anomalies in real time, particularly in large and remote plantation areas. Consequently, boundary marker displacement is often identified only after significant issues have occurred. To address this challenge, an IoT-based monitoring system can provide continuous tracking of marker position and orientation, enabling real-time detection of displacement and manipulation events.

Manual inspections are periodic, costly, and unable to detect boundary marker displacement in real time. Existing monitoring approaches also lack continuous surveillance and immediate alert capabilities. To address these limitations, this study proposes an IoT-based Smart Pole system that integrates GNSS positioning, HMC5883L orientation sensing, LoRa communication, and cloud-based monitoring. The system continuously tracks the position and orientation of boundary markers and automatically generates alerts when displacement or manipulation is detected, enabling timely intervention and improved plantation asset security.

This study aims to develop an IoT-based Smart Pole system for autonomous boundary marker monitoring using solar-powered operation. The system integrates GNSS positioning, LoRa communication, geofencing, and an IoT dashboard to enable continuous, long-range, and real-time monitoring of marker position and orientation. By providing early detection of displacement and manipulation events, the proposed system is expected to improve monitoring efficiency, reduce the risk of land disputes, and support digital transformation in plantation asset management.

Although previous studies as shown in Table 1 have explored GNSS-based tracking, LoRa communication, or IoT monitoring independently, limited research has integrated displacement detection, orientation change monitoring, long-range wireless communication, and autonomous solar-powered operation into a single system for boundary marker monitoring. This gap highlights the need for a comprehensive solution capable of providing continuous and real-time protection of plantation boundary markers.

However, the proposed approach also has several limitations that indicate areas for further research. The

TABLE I
COMPARISON OF RELATED IOT-BASED MONITORING SYSTEMS

Study	Application	Sensor	Communication	Limitation	Difference from This Work
Alhasnawi, Bilal Naji; et al.	IoT for Smart Precision Agriculture	IoT	Wi-Fi / LoRa	Long term power consumption and energy efficiency analysis were not addressed in this study	Cellular IoT communication for remote plantation deployment
Shen, Nan; et al.	Bayesian Inference & GNSS RTK	GNSS RTK	GNSS RTK	Short term monitoring scope	GNSS receiver, magnetometer, and battery monitoring
Lee, Huang Chen & Ke, Kai Hsiang	Large area IoT sensor monitoring	LoRa	LoRa Mesh Network	No positioning or location tracking capability is implemented	Automatic manipulation detection and alarm generation
Sadowski, Sebastian & Spachos Petros	Smart agriculture and environmental monitoring for precision farming	Solar Panel	Solar Panel	Only for monitoring and not support asset security	Real time alarms and web based notifications
Abbas, A.H; et al.	Vehicle tracking and anti theft monitoring using GPS and geofencing technology	GPS Module (NEO-6M)	Wi-Fi	The system is designed specifically for vehicle tracking	Plantation boundary marker monitoring
Wang, Yan; et al.	Indoor pedestrian positioning and navigation and learning based inertial odometry	IMU Sensors Combined with a Magnetometer	Data are processed locally	It does not utilize GNSS positioning, making it unsuitable for large outdoor planation areas	Using cellular IoT (SIM7600)

system detects physical manipulation of boundary markers but does not identify or determine the responsible actor. In addition, GNSS positioning accuracy may be affected by environmental conditions, such as signal obstructions and surrounding terrain. The performance of wireless communication may also depend on network availability, terrain characteristics, and the physical environment surrounding the monitoring area. Furthermore, the system has been evaluated using a limited number of prototypes and within limited testing areas, which may affect the generalizability of the results to larger and more diverse plantation environments. The proposed system is intended to support early detection of boundary marker displacement and assist field monitoring activities. It is not intended to replace certified cadastral surveying instruments.

II. Research Methodology

The monitoring system is designed using a Master-Slave topology based on LoRa communication to optimize energy efficiency and bandwidth utilization [3]. The Smart Pole system operates under a Master-Slave communication architecture as shown in Fig. 1, with the ESP32-C3 microcontroller serving as the main processing unit. At the node level, the Slave Pole is responsible for acquiring physical condition data of the boundary marker through an HMC5883L magnetometer sensor, which detects three-axis orientation and heading changes, and a uBlox NEO-M8N GPS module for coordinate tracking [4]. The collected sensor data are transmitted to the Master Pole using an Ebyte E32 LoRa communication module. The operating principle of the system is shown in Fig. 2 and Fig. 3.

Acting as the network coordinator, the Master Pole aggregates data from all connected nodes, performs data parsing, and forwards the processed information to a database server via a cellular network using the SIM7600G-H communication module. All boundary marker information is then visualized through an interactive web-based dashboard utilizing the Leaflet digital mapping library.

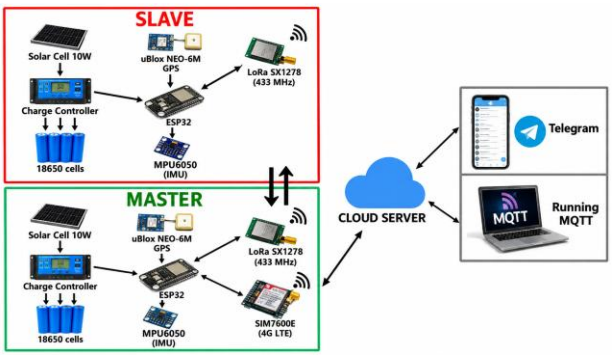


Fig. 1 Block diagram of the proposed master-slave IoT monitoring system

To detect boundary marker displacement, the system employs the Haversine method to calculate the distance between the current GPS coordinates and the predefined reference coordinates. Furthermore, a geofencing technique is implemented by defining a virtual boundary around the original marker location. When the calculated displacement exceeds the predefined geofence radius, the system identifies the condition as a potential manipulation event. As a rapid response mechanism, the system automatically triggers notifications to users via Telegram whenever the boundary marker moves outside the designated geofence area. This approach enables timely detection of boundary marker manipulation and supports proactive monitoring of land boundaries.

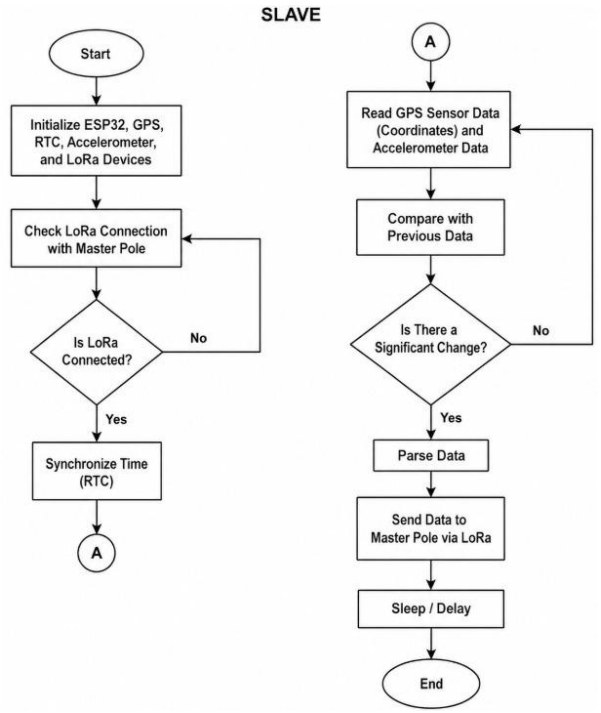


Fig. 2. Flowchart of the slave node operation for sensor data acquisition

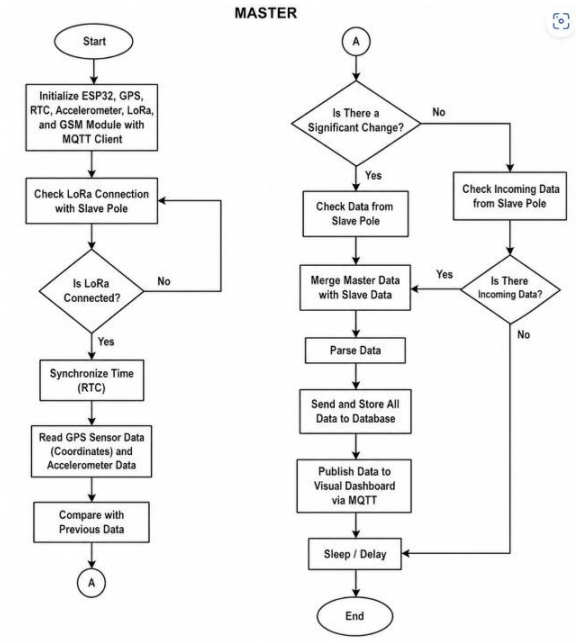


Fig. 3 Flowchart of the master node operation for sensor data acquisition

The system starts by initializing the GPS, magnetometer/IMU, LoRa, and cellular modules, followed by storing the baseline coordinates and orientation as reference data. During operation, the system periodically acquires current GPS and orientation measurements, calculates displacement using the Haversine formula, and determines orientation changes relative to the baseline. Battery voltage is also monitored. The measured values are compared with predefined thresholds to detect boundary marker manipulation. The system then transmits the status to the server and sends a Telegram alert when a threshold violation is detected. Finally, the device enters sleep mode to minimize power consumption before repeating the monitoring cycle.

A. Haversine Method

The Haversine method is a widely used algorithm for calculating the shortest distance between two points on the Earth's surface based on their geographical coordinates, namely latitude and longitude. In this study, the Haversine formula is employed to determine the displacement distance of plantation boundary markers by comparing the initial reference coordinates with the current coordinates obtained from the GPS sensor.

The method assumes that the Earth is a sphere with an average radius of 6,371 km and computes the great-circle distance between two geographical points. Due to its simplicity and sufficient accuracy for location-based applications, the Haversine method is suitable for real-time displacement monitoring in IoT-based systems. The Haversine distance is calculated as follows:

$$d = 2R \cdot \arcsin\left(\sqrt{\sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos(\varphi_1)\cos(\varphi_2)\sin^2\left(\frac{\Delta\lambda}{2}\right)}\right) \quad (1)$$

where d is the distance between two points in meters, R is the Earth's radius (6,371,000 m), $\varphi_1$and φ_2 are the latitudes, and λ_1 and λ_2 are the longitudes of the two points in radians, with $\Delta\varphi=\varphi_2-\varphi_1$ and $\Delta\lambda=\lambda_2-\lambda_1$. In the proposed Smart Pole system, the initial coordinates of each boundary marker are stored as baseline data. Subsequently, the current GPS coordinates acquired by the u-blox NEO-M8N module are periodically compared with the baseline coordinates using the Haversine formula to estimate the displacement distance.

B. Geofencing Method

Geofencing is a location-based monitoring technique that defines a virtual boundary around a specific geographic area. In this study, geofencing is implemented to determine whether a plantation boundary marker remains within an allowable area or has been displaced beyond a predefined threshold. The geofence is established by defining the initial position of the boundary marker as the center point and assigning a predefined radius as the allowable displacement limit. The displacement distance calculated using the Haversine method is then compared with the geofence radius to determine the status of the boundary marker. With geofence radius r, the geofencing decision rule can be expressed as:

$$Status = \begin{cases} Normal, & \text{if } d \le r \\ Alert, & other \end{cases} \quad (2)$$

If the calculated displacement distance remains within the geofence radius, the boundary marker is considered to

TABLE I
RESULTS OF GPS-BASED POLE DISPLACEMENT DETECTION

Trial	Reference Lat	Reference Lon	Measured Lat	Measured Lon	Error (m)
N-5m	-2.548926	118.014863	-2.548881	118.014861	1.2
N-10m	-2.548926	118.014863	-2.548835	118.014867	1.4
N-15m	-2.548926	118.014863	-2.548791	118.014860	1.6
N-20m	-2.548926	118.014863	-2.548747	118.014865	1.8
N-25m	-2.548926	118.014863	-2.548700	118.014868	2.0
E-5m	-2.548926	118.014863	-2.548924	118.014910	1.1
E-10m	-2.548926	118.014863	-2.548927	118.014956	1.3
E-15m	-2.548926	118.014863	-2.548925	118.015001	1.5
E-20m	-2.548926	118.014863	-2.548923	118.015047	1.7
E-25m	-2.548926	118.014863	-2.548928	118.015093	1.9
S-5m	-2.548926	118.014863	-2.548972	118.014861	1.3
S-10m	-2.548926	118.014863	-2.549016	118.014866	1.5
S-15m	-2.548926	118.014863	-2.549060	118.014864	1.7
S-20m	-2.548926	118.014863	-2.549106	118.014862	1.9
S-25m	-2.548926	118.014863	-2.549150	118.014865	2.1
W-5m	-2.548926	118.014863	-2.548925	118.014815	1.2
W-10m	-2.548926	118.014863	-2.548927	118.014770	1.4
W-15m	-2.548926	118.014863	-2.548924	118.014725	1.6
W-20m	-2.548926	118.014863	-2.548928	118.014678	1.8
W-25m	-2.548926	118.014863	-2.548926	118.014633	2.0

be in a normal condition. Conversely, if the displacement distance exceeds the predefined threshold, the system classifies the event as a potential manipulation or displacement and generates an alert notification. The alert information is subsequently transmitted to the cloud server and forwarded to users via the Telegram messaging platform for real-time monitoring. The integration of Haversine distance computation and geofencing enables the proposed Smart Pole system to provide accurate and real-time detection of plantation boundary marker displacement, thereby enhancing monitoring efficiency and asset security.

III. Result and Discussion

A. GPS-Based Pole Displacement Detection

The functionality testing of the uBlox NEO-M8N GPS sensor was conducted to evaluate the accuracy of geographic coordinate measurements, including latitude and longitude, by comparing the obtained data with reference coordinates from a consumer grade smartphone GPS. The objective of this test was to assess the sensor's capability to provide reliable positioning information for Smart Pole monitoring applications. Based on the experimental results, the comparison between the coordinates measured by the uBlox NEO-M8N GPS module and the reference coordinates is presented in Table II. The spatial distribution of the GPS measurements at distances of 5, 10, 15, 20, and 25 m in the north, south, east, and west directions is illustrated in Fig. 4, showing the consistency of the measured positions relative to the predefined reference points.

Based on the experimental analysis, the sensor measurement error percentage in total is 10.67%. The observed error fluctuations were relatively small and remained stable across all testing points, with no significant deviations recorded. These results indicate that the uBlox NEO-M8N GPS sensor is capable of consistently detecting positional changes on a meter-scale level. Therefore, the sensor is considered suitable for implementation in a land boundary marker displacement monitoring system.

TABLE II
SUMMARY GPS-BASED POLE DISPLACEMENT DETECTION TESTING

Parameter	Value	Unit
Mean error	1.60	m
Standard Deviation	0.32	m
MAE	1.60	m
RMSE	1.63	m
Maximum Error	2.10	m

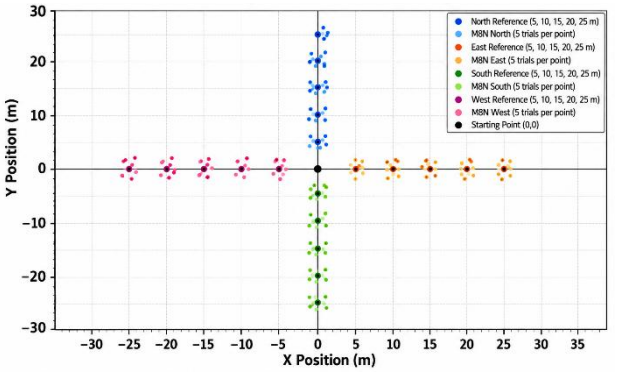


Fig. 4. GPS-Based Pole Displacement Detection Graph

B. Gyroscope-Based Pole Displacement Detection Testing

The functionality testing of the HMC5883L magnetometer sensor was carried out to evaluate the accuracy of orientation (heading) and magnetic field measurements along the three axes (X, Y, and Z). The sensor readings were compared with measurements obtained from a certified smartphone digital compass used as the reference standard. Prior to testing, the system underwent both hard-iron and soft-iron calibration procedures to minimize the effects of environmental

magnetic interference and improve measurement accuracy. The results of the post-calibration magnetometer testing are presented in Table IV.

TABLE III
GYROSCOPE-BASED POLE DISPLACEMENT DETECTION TESTING

Actual Rotation	Trials	Mean Measured Heading Change (°)	MAE (°)	RMSE (°)	Detection Status
0 deg	30	0.8	0.80	0.95	Normal
15 deg	30	14.2	0.80	1.05	Normal / Alert
30 deg	30	29.1	0.90	1.15	Alert
45 deg	30	44.0	1.00	1.25	Alert
90 deg	30	88.3	1.70	2.05	Alert

TABLE IV
TEST RESULT SOLAR POWER SYSTEM PERFORMANCE TESTING

Time	Panel Voltage (V)	Panel Current (A)	Power (W)	Battery Voltage (V)	Charging Current (A)	Panel Temp (°C)
08:00	17.8	0.62	11.04	12.3	0.75	29
10:00	18.4	1.12	20.61	12.7	1.35	37
12:00	18.1	1.65	29.87	13.2	1.95	48
14:00	17.9	1.48	26.49	13.5	1.72	46
16:00	17.3	0.81	14.01	13.7	0.93	35

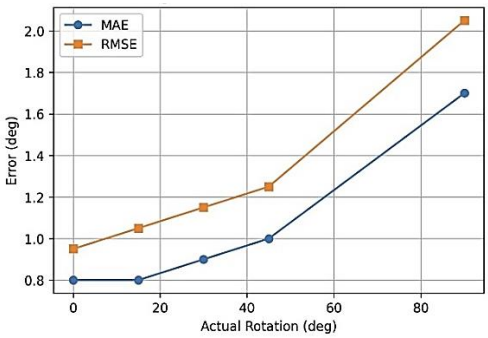


Fig. 5. Gyroscope-Based Pole Displacement Detection Testing Graph

Table IV and Fig. 5 show the heading measurement performance of the HMC5883L magnetometer at rotation angles of 0°, 15°, 30°, 45°, and 90°. The sensor demonstrated good agreement between the actual and measured heading changes, with mean measured values of 0.8°, 14.2°, 29.1°, 44.0°, and 88.3°, respectively. The MAE ranged from 0.80° to 1.70°, while the RMSE ranged from 0.95° to 2.05°.

As shown in Fig. 5, both MAE and RMSE increased slightly with larger rotation angles, which is expected due to sensor noise and magnetic disturbances. The corresponding percentage error ranged from 1.89% to 5.33%, with an average error of 3.11%, indicating an overall measurement accuracy of approximately 96.89%. Despite this increase, the maximum RMSE remained below 2.1°, demonstrating acceptable measurement accuracy for practical deployment.

In terms of detection performance, the system successfully identified orientation changes of 30°, 45°, and 90° as manipulation events, while 0° remained in the normal condition and 15° was near the alert threshold. Overall, the results confirm that the HMC5883L provides reliable orientation monitoring for detecting boundary marker manipulation in the proposed Smart Pole system..

C. Solar Power System Performance Testing

The 30 Wp solar panel testing was conducted to evaluate the performance of solar energy conversion into electrical energy and to analyze the charging characteristics of a 12 V 7.5 Ah Sealed Lead-Acid (SLA) battery under real field conditions. The objective of this test was to determine the capability of the solar power system to provide a sustainable energy supply for the Smart Pole monitoring system, ensuring continuous operation in remote locations without dependence on the conventional power grid. The current consumption profile of the system components is presented in Table V.

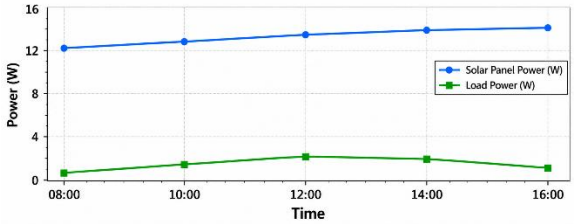


Fig. 6 Solar Power System Performance Graph

Table V and Fig. 6 show the performance of the solar-powered subsystem during the charging period. The solar panel output increased from 11.04 W at 08:00 to a peak of 29.87 W at 12:00, corresponding to the highest panel current of 1.65 A. Similarly, the charging current reached a maximum of 1.95 A at midday before decreasing in the afternoon due to reduced solar irradiance.

D. LoRa Communication Performance Testing

The testing of the LoRa EBYTE E32 radio frequency module was conducted to evaluate the reliability of the wireless communication network between boundary marker nodes. The assessment focused on transmission success rate, data packet consistency, and communication delay under various transmission distances and environmental obstacle conditions. The transmission success rate and delay performance parameters are summarized in Table VI.

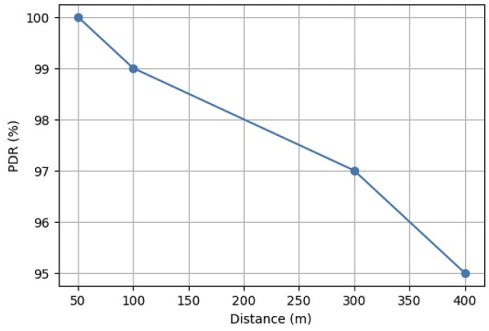


Fig. 7 LoRa Communication Performance Graph

TABLE V
TEST RESULT LORA COMMUNICATION PERFORMANCE

Distance	Environment	Tx Packets	Rx Packets	PDR (%)	Avg Latency (ms)	RSSI (dBm) / SNR (dB)
50 m	Open	100	100	100.0	45	-67 / 9
100 m	Open	100	99	99.0	52	-72 / 8
300 m	Semi closed	100	97	97.0	68	-85 / 6
400 m	Semi closed	100	95	95.0	82	-91 / 4

TABLE VI
TEST RESULT CELLULAR COMMUNICATION PERFORMANCE

Location	Signal Quality	Network Type	Packets Sent	Success Rate (%)	Server Latency (s)	Telegram Alert Latency (s)	Retry Count
Open Area	Good	4G LTE	100	100	1.2	2.0	0
Semi Enclosed	Moderate	4G LTE	100	98	2.1	3.4	2
Enclosed / Obstructed	Poor	3G / Weak LTE	100	93	4.8	7.2	7

TABLE VII
INTEGRATED SYSTEM TESTING RESULTS

Scenario	Expected Status	Measured Response	Alert Latency (s)	Pass / Fail
Normal pole, no movement	Normal	No alarm generated during 8 hour observation period	N/A	Pass
GPS displacement > threshold (5m)	Manipulated	Dashboard status changed to “Manipulated” and Telegram alert received	7.2	Pass
Direction change > threshold (20º)	Manipulated	HMC5883L detected significant heading change, dashboard updated, Telegram alert received	6.1	Pass
Low battery (<20%)	Warning	Low battery notification displayed on dashboard and Telegram	4.6	Pass
Temporary communication loss	Recovered / Warning	Data transmission interrupted for 60 s and automatically recovered after network restoration	12.4	Pass

Table VI and Fig. 7 show the communication performance of the LoRa EBYTE E32 module at distances ranging from 50 m to 400 m. The PDR decreased slightly from 100% at 50 m to 95% at 400 m, while the average latency increased from 45 ms to 82 ms. Signal quality also declined with distance, as indicated by RSSI values decreasing from −67 dBm to −91 dBm and SNR values decreasing from 9 dB to 4 dB. Despite these reductions, the module maintained reliable communication with an average PDR of 97.75% and an average packet loss of only 2.25%. These results demonstrate that the LoRa EBYTE E32 is suitable for long-range Smart Pole monitoring applications in plantation environments.

E. Cellular Communication Performance Testing

The functionality testing of the SIM7600G-H cellular communication module was conducted to evaluate the reliability of aggregated data transmission, including GPS coordinates and boundary marker orientation information, from the Master Pole to the centralized database server. The objective of this test was to assess the module’s capability to provide stable internet connectivity and ensure successful data delivery for remote monitoring applications. The testing results are presented in Table VII.

Table VII and Fig. 8 show the performance of the SIM7600G-H cellular gateway under different signal conditions. The success rate decreased from 100% in the open area to 93% in the enclosed/obstructed environment, while server latency increased from 1.2 s to 4.8 s and Telegram alert latency increased from 2.0 s to 7.2 s. The retry count also increased as signal quality deteriorated. The communication error increased from 0% to 7%, with an average error of *3.0%* and an average success rate of *97.0%*. Overall, the results demonstrate that the SIM7600G-H provides reliable data transmission and alert delivery for Smart Pole monitoring applications under varying network conditions.

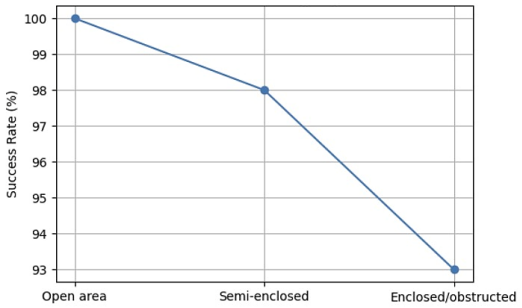


Fig. 8 Test Result Cellular Communication Performance Graph

F. Integrated System Testing Results

Table VIII presents the results of the integrated system testing conducted to evaluate the overall functionality and response of the proposed IoT based smart pole system under several operating scenarios. The testing covers normal operation, GPS based displacement detection, heading direction changes, low battery conditions, and temporary communication loss. Under the normal operating condition, where the pole experienced no movement, the system remained in the normal state and no alarm was generated during the 8 hour observation period. This result indicates that the system was able to maintain

stable operation without generating false alerts when no abnormal condition occurred. In the GPS displacement threshold scenario, the pole was displaced beyond the predefined 5 m threshold. The system successfully detected the displacement, changed the dashboard status to "Manipulated", and generated a Telegram notification. The measured alert latency was 7.2 s, demonstrating that the system could identify significant positional changes and deliver an alert to the user.

The selection of 5m as the testing threshold was based on the physical accuracy limitations of the uBlox NEO-M8N GPS module, which demonstrated a mean positioning error of 1.60 m and a maximum error of 2.10 m. Setting the geofencing threshold at 5m provides a necessary safety margin to account for natural satellite signal drift and environmental noise, ensuring that false alarms are minimized while still reliably capturing true physical displacements of the boundary marker. For the heading direction change scenario, a change exceeding the predefined 20° threshold was introduced. The HMC5883L magnetometer successfully detected the change in heading direction, resulting in an updated "Manipulated" status on the dashboard and the transmission of a Telegram alert. The recorded alert latency was 6.1 s. This confirms that the system can detect manipulation not only through positional displacement but also through changes in the pole's orientation.

The 20° threshold was selected because minor angular variations below 15° can occur naturally due to sensor noise (with the HMC5883L having an average error of 3.11% and an RMSE up to 2.05°), wind vibrations, or slight structural settling. A 20° deviation serves as a clear indicator of intentional physical tampering such as rotating, tilting, or uprooting the pole while remaining sensitive enough to catch unauthorized orientation changes before significant positional displacement occurs. The low battery scenario, defined as a battery level below 20%, was also successfully detected. The system displayed a low battery warning on the dashboard and sent a corresponding Telegram notification with an alert latency of 4.6 s. This feature enables users to identify potential power related issues before they affect system operation. Finally, the temporary communication loss scenario was tested by interrupting data transmission for approximately 60 s. The system successfully recovered communication after the network was restored, with a measured response latency of 12.4 s. The system was therefore able to handle temporary communication failures and automatically resume data transmission after network recovery. Overall, all tested scenarios achieved a Pass result, indicating that the integrated system successfully performed its intended monitoring, detection, notification, and recovery functions. The alert latency for the abnormal conditions ranged from 4.6 s to 12.4 s, demonstrating that the system is capable of providing relatively fast notifications while maintaining reliable operation under different fault and manipulation scenarios.

IV. Conclusion

This study successfully developed and evaluated an IoT-based Smart Pole system for real-time monitoring of plantation boundary markers. The proposed system integrates GNSS positioning, HMC5883L orientation sensing, LoRa EBYTE E32 communication, a SIM7600G-H cellular gateway, solar-powered operation, and cloud-based monitoring to detect displacement and manipulation events. Experimental results demonstrated that the GPS NEO-M8N achieved an average positioning error of 1.60 m, corresponding to an overall accuracy of 89.33%. The HMC5883L magnetometer provided reliable orientation measurements with an average error of 3.11%, a maximum MAE of 1.70°, and a maximum RMSE of 2.05°. Communication testing showed that the LoRa EBYTE E32 maintained an average PDR of 97.75% with only 2.25% packet loss at distances up to 400 m, while the SIM7600G-H cellular gateway achieved an average success rate of 97.0% with an average communication error of 3.0% under varying signal conditions.

The solar power subsystem, consisting of a 30 W photovoltaic panel and a 12 V 7.5 Ah SLA battery, provided stable autonomous operation, with battery voltage increasing from 12.3 V to 13.7 V during the charging period. Integrated system testing further confirmed the capability of the proposed system to detect boundary marker displacement and orientation changes, visualize monitoring data through a web dashboard, and deliver timely Telegram alerts.

Overall, the results demonstrate that the proposed Smart Pole system is a feasible, reliable, and energy-autonomous solution for continuous boundary marker monitoring in plantation environments. However, the evaluation was limited to prototype-scale deployment and short-term field testing. Future work should focus on long-term operation, larger deployment areas, and further optimization of positioning accuracy and communication reliability under diverse environmental conditions.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Declaration of Artificial Intelligence (AI) Usage

During the preparation of this manuscript, the author(s) used Artificial Intelligence (AI) tools, including ChatGPT developed by OpenAI, to assist in language refinement, grammar correction, text organization, and improving the clarity of written content. The author(s) carefully reviewed, edited, and validated all AI-generated outputs and take full responsibility for the content, accuracy, and integrity of the manuscript. No AI tool was used to generate, manipulate, or analyze the research data, results, or conclusions presented in this study.

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