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GPS-Based Proximity Detection System Between Ship and Buoy for Marine Navigation

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Abstract – *Maritime navigation safety remains a major concern, especially for small vessels that lack advanced navigation aids such as radar or AIS. This study proposes a proximity detection system between a ship and a buoy using GPS data, LoRa communication, and ThingsBoard visualization. The ship node periodically transmits its coordinates through LoRa. In contrast, the buoy node receives the ship position, reads its own GPS coordinates, calculates the separation distance using the Haversine formula, and determines the system status as SAFE or ALERT based on a 50 m threshold. The processed telemetry is then forwarded to a gateway and visualized in real time on ThingsBoard. Experiments were conducted at distances of 10-100 m under two scenarios, with and without an obstacle. In the open-area condition, the system achieved an average percentage error of 3.42%, a mean absolute error (MAE) of 1.82 m, and a root mean square error (RMSE) of 2.47 m. Under obstacle conditions, the average percentage error increased to 24.07%, with MAE and RMSE values of 6.36 m and 6.93 m, respectively. Communication performance remained stable, with a 200-230 ms delay, RSSI values in the good category, and packet loss between 0% and 10%. These results show that the proposed system can provide an affordable early-warning solution for ship-buoy proximity monitoring.*

***Keywords**: GPS, Haversine, LoRa, Maritime Navigation, Proximity Detection*

I. Introduction

Indonesia is one of the world's largest archipelagic nations, with more than 17,000 islands and a very long coastline. As a result, sea transportation plays an important role in logistics distribution, regional connectivity, and public mobility. According to Statistics Indonesia, maritime transportation handled nearly 300 million tons of goods and more than 17 million passengers in 2023 [1]. Despite this high level of activity, the adoption of integrated safety systems is still limited, especially on small vessels. The annual SAR report also shows that marine accidents remain a serious issue, and many cases are associated with navigational limitations and operator error [2], [3].

One important challenge in maritime safety is the lack of an automatic warning system that alerts operators when a vessel approaches a navigation aid, such as a buoy. A buoy serves as a marker for safe routes, navigational boundaries, and hazardous areas. In low-visibility conditions, at night, or in busy waterways, a vessel may approach a buoy too closely before the operator becomes aware of the risk. For this reason, a practical warning system is needed, particularly for small vessels that do not use radar or AIS. In this study, low-cost GPS Neo-6M modules are used to obtain latitude and longitude data, while LoRa is selected for long-range, low-power communication [4], [5].

Several previous studies have explored the use of GPS and LoRa for maritime or mobile tracking applications. Sa'adah et al. developed a LoRa-based smart buoy tracking system, but their work focused on buoy position monitoring rather than ship–buoy proximity detection [6]. Fauzi et al. applied the Haversine formula to a land-based mobile location-search application [7], while Hasan et al. used GPS for online ship position monitoring [8]. Other studies have also examined real-time monitoring systems that combine LoRa and visual interfaces [9], [10]. Although these works demonstrate the feasibility of GPS-based monitoring, they do not implement an on-node distance calculation and alert mechanism specifically for ship–buoy safety.

Based on this research gap, the present paper proposes an Internet of Things (IoT)-based system that integrates GPS, LoRa, the Haversine formula, and ThingsBoard. The main contribution of this study is to place the proximity-processing function directly on the buoy node. With this arrangement, the buoy can receive the ship's location, calculate the distance, classify the condition as SAFE or ALERT, and forward the telemetry to the gateway and dashboard. The remainder of this paper is organized as follows: Section II explains the system design and methods, Section III describes the experimental setup, Section IV presents the results and discussion, and Section V concludes the paper.

II. System Design

A. *Proposed System Architecture*

The proposed system consists of three main parts: the ship node, the buoy node, and the gateway. The ship node periodically reads its position using a GPS Neo-6M module. The acquired latitude and longitude values are packaged into a LoRa payload and transmitted to the buoy node. The buoy node functions as the main processing unit. It receives the ship coordinates, reads its own coordinates, and calculates the distance using the Haversine formula. Based on a 50 m threshold, the buoy determines whether the condition is SAFE or ALERT. Finally, the processed data are sent to the gateway and uploaded to ThingsBoard via MQTT for real-time monitoring.

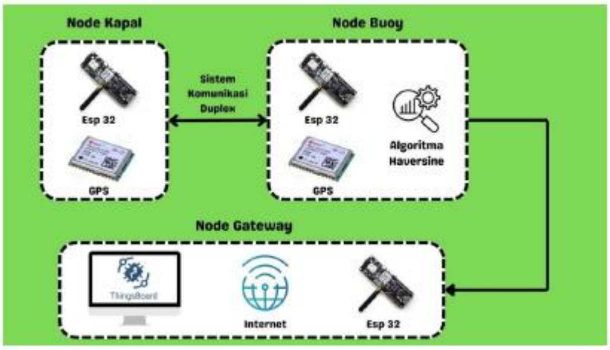


Fig. 1. Proposed system architecture for ship-buoy proximity monitoring

B. *Hardware Configuration*

The hardware platform is built around TTGO ESP32 LoRa boards, GPS Neo-6M modules, 915 MHz LoRa antennas, and a Li-ion 18650 battery system with TP4056 charging support. The ESP32 handles sensor acquisition, LoRa communication, telemetry processing, and dashboard integration. LoRa is suitable for maritime monitoring because it supports long-range wireless communication, consumes relatively low power, and maintains reliable signal performance. The hardware wiring used in this study is illustrated in Fig. 2, while the main components are summarized in Table I.

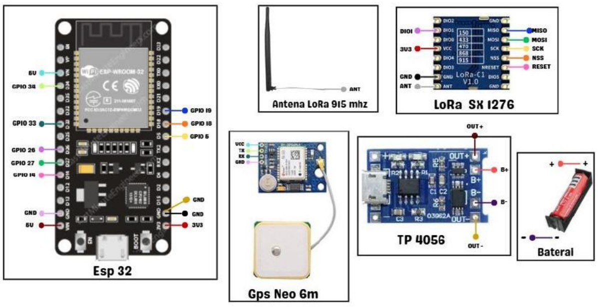


Fig. 2. Hardware wiring configuration of the proposed system

TABLE I
MAIN HARDWARE COMPONENTS USED IN THE PROPOSED SYSTEM

Component	Main Function	Specification / Notes
TTGO ESP32 LoRa	Main controller	ESP32 with integrated LoRa SX1276
GPS Neo-6M	Position acquisition	Approx. +-2.5 to +-5 m accuracy
LoRa antenna 915 MHz	Wireless link	Outdoor communication support
Li-ion 18650 + TP4056	Portable power supply	Rechargeable battery system
ThingsBoard	Visualization and storage	Real-time dashboard via MQTT

C. *Distance Computation and Evaluation Metrics*

The distance between the ship and the buoy is calculated on the buoy node using the Haversine formula. This method estimates the shortest surface distance between two geographic points using their latitude and longitude, while remaining lightweight enough to run directly on the ESP32-based buoy node. Before the distance is computed, all coordinate values in degrees are converted to radians.

$$\text{Radian} = \text{derajat x } \frac{\pi}{180} \tag{1}$$

$$a = sin^2(\frac{\Delta\phi}{2}) + cos\,\phi_1\,cos\,\phi_2\,sin^2(\frac{\Delta\lambda}{2}) \tag{2}$$

$$c = 2 \cdot atan2\frac{(\sqrt(a\,)}{\sqrt{(1-a)}} \tag{3}$$

$$d = R\,.\,c \tag{4}$$

$$\Delta\phi = \phi_2 - \phi_1 \tag{5}$$

$$\Delta\lambda = \lambda_2 - \lambda_1 \tag{6}$$

where:

a = haversine parameter
c = central angle between two points
d = distance between the ship and buoy (m)
R = earth's radius = 6,371,000 (m)
$\emptyset_1$ = latitude of the first point (radian)
$\emptyset_2$ = latitude of the second point (radian)
λ_1 = longitude of the first point (radian)
λ_2 = longitude of the second point (radian)

A manual Haversine calculation was also carried out using the first coordinate pair from the experiment to verify the implementation. The coordinates are ship = (-

7.276274°, 112.794624°) and buoy = (-7.276304°, 112.794717°).

$$\phi_1 = -7.276274\,x\,\frac{\pi}{180} = -0.126995 \tag{7}$$

$$\phi_2 = -7.276274\,x\,\frac{\pi}{180} = -0.126995 \tag{8}$$

$$\lambda_1 = 112.794624\,x\,\frac{\pi}{180} = 1.968638 \tag{9}$$

$$\lambda_2 = 112.794717\,x\,\frac{\pi}{180} = 1.968639 \tag{10}$$

Next, calculate the difference in latitude and longitude between the two points:

$$\Delta\phi = -0.126995 - (-0.126995) = -0.00000052 \tag{11}$$

$$\Delta\lambda = 1.968639 - 1.968638 = 0.00000162 \tag{12}$$

where:
$\Delta\phi$ = difference in latitude
$\Delta\lambda$ = difference in longitude

That value is then substituted into the Haversine formula:

$$a = sin^2(\frac{\Delta{-0.00000052}}{2}) + cos\,(-0.127)\,cos\,(-0.127)\,sin^2(\frac{\Delta{-0.00000162}}{2})$$

$$a \approx 6.76x10^{-14} + (0.992)^2\,x\,6.56x10^{-13}$$

$$a \approx 7.13x10^{-13} \tag{13}$$

The distance between the ship and the buoy is then calculated using the following equation:

$$d = 2\,x\,6371000\,x\,arcsin\left(\sqrt{7.13x10^{-13}}\right)$$

$$d = 10.78\,meter \tag{14}$$

The manual result of 10.78 m is consistent with the first system measurement, confirming that the distance computation implemented on the buoy node follows the intended Haversine procedure.

The measurement accuracy is evaluated separately using Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and percentage error. MAE describes the average magnitude of error, while RMSE emphasizes larger deviations; therefore, both metrics are reported independently in this paper.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{15}$$

where:
n = number of test samples
y_i = actual distance of the i-th sample
$\hat{y}_i$ = measured distance of the i-th sample
$|y_i - \hat{y}_i|$ = absolute error

MAE represents the average absolute difference between the actual distance and the distance produced by the system. A lower MAE indicates better overall agreement. In (7), *n* is the number of test samples, y_i is the actual distance, and $\hat{y}_i$ is the distance measured by the system.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{16}$$

where:
n = number of test samples
y_i = actual distance of the i-th sample
$\hat{y}_i$ = measured distance of the i-th sample
$(y_i - \hat{y}_i)^2$ = squared error

RMSE gives the square root of the average squared error and is more sensitive to large deviations than MAE. This makes RMSE useful for identifying whether some measurements produce significantly higher error. In (8), *n*, y_i, and $\hat{y}_i$ have the same meanings as in the MAE equation.

$$Error(\%) = \left|\frac{y_i - \hat{y}_i}{y_i}\right|\,x\,100 \tag{17}$$

where:
y_i = actual distance
$\hat{y}_i$ = measured distance

The percentage error indicates the relative deviation between the actual distance and the system distance for each experiment. Smaller percentage values correspond to higher accuracy. In the proposed system, the warning logic uses a 50 m threshold; therefore, the status becomes ALERT when the computed distance is 50 m or less and remains SAFE when the distance is greater than 50 m.

D. Haversine Flowchart and Telemetry Workflow

The Haversine computation flowchart, adopted from the final project report, is presented in Fig. 3. The flow starts by reading two coordinate pairs, converting latitude and longitude from degrees to radians, calculating Δφ and Δλ, evaluating the Haversine parameter a, obtaining the central angle c, and finally computing the distance *d*. Because the procedure does not require iterative processing, it is suitable for real-time execution on the buoy node.

In the implemented telemetry workflow, the ship node reads GPS data and transmits its coordinates through LoRa every 10 s. The buoy node receives the ship's position, reads its own GPS coordinates, applies the Haversine steps shown in Fig. 3, compares the result against the 50 m threshold, and sends back the SAFE or ALERT status. The same telemetry packet is then forwarded to the gateway and published to ThingsBoard for remote monitoring.

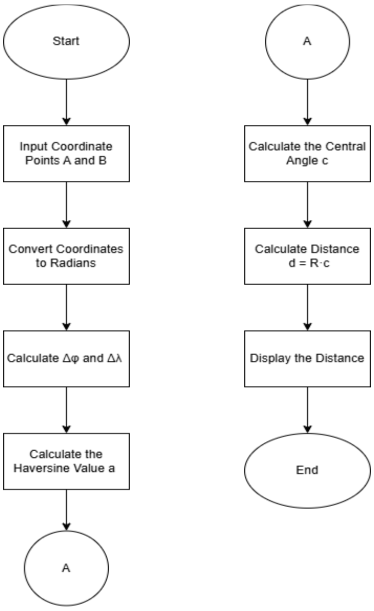


Fig. 3. Haversine computation flowchart adopted from the final project report

III. Experimental Setup

The system was tested in an open area around the Politeknik Elektronika Negeri Surabaya (PENS) campus to emulate a clean outdoor environment with adequate GPS reception and LoRa propagation. The distance between the ship node and the buoy node was varied from 10 m to 100 m. Two test scenarios were considered: an open-area condition without an obstacle and a condition with an obstacle, where a person passing between the nodes represented a temporary physical obstruction. The transmission interval was set to 10 s, and the LoRa frequency was 915 MHz. This test configuration was selected to evaluate both the accuracy of the distance computation and the system's overall communication performance.

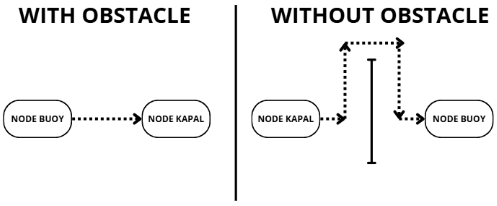


Fig. 4. Ship node and buoy node test setup under without-obstacle and with-obstacle conditions

The telemetry generated by the buoy node includes ship latitude, ship longitude, buoy latitude, buoy longitude, computed distance, system status, GPS fix information, RSSI, and timing information. The main evaluation metrics are percentage error between the actual and system distances, MAE, RMSE, communication delay, RSSI, and packet loss. A manual Haversine calculation using one of the tested coordinate pairs yielded a distance of approximately 10.78 m, matching the first system result and confirming that the implemented formula works correctly.

IV. Results and Discussion

A. Distance Accuracy Without Obstacle

Table II presents the distance results in the open-area condition. The system shows good agreement with the actual distance, with the largest error at 10 m and the smallest at 80 m. The average percentage error is 3.42%, while MAE and RMSE are 1.82 m and 2.47 m, respectively. These values indicate that the proposed design performs reliably in a line-of-sight condition and is appropriate for a 50 m early-warning threshold.

TABLE II
DISTANCE MEASUREMENT RESULTS WITHOUT OBSTACLE

No.	Actual (m)	System (m)	Error (%)
1.	10	10.78	7.80
2.	20	20.29	1.45
3.	30	30.71	2.37
4	40	40.28	0.70
5.	50	52.65	5.30
6.	60	61.99	3.31
7.	70	73.56	5.09
8.	80	80.02	0.02
9.	90	87.70	2.56
10.	100	94.43	5.57

B. Distance Accuracy With Obstacle

Table III summarizes the measurements obtained when an obstacle was present between the nodes. Under this condition, the average percentage error increased to 24.07%, and the largest deviation was observed at 10 m. This degradation is mainly caused by GPS instability, multipath effects, and the limited short-range accuracy of the Neo-6 M. Even so, the system still provides useful estimates at medium distances, and the resulting safety status remains usable for practical monitoring.

TABLE III
DISTANCE MEASUREMENT RESULTS WITH OBSTACLE

No.	Actual (m)	System (m)	Error (%)
1.	10	22.12	121.20
2.	20	29.81	49.05
3.	30	27.33	8.90
4	40	33.79	15.53
5.	50	55.88	11.76
6.	60	64.96	8.27
7.	70	76.54	9.34
8.	80	82.71	3.39
9.	90	84.58	6.02
10.	100	92.74	7.26

C. Distance Accuracy With Obstacle

In addition to distance accuracy, the communication performance of the LoRa link was also evaluated. In both scenarios, the communication delay remained within the normal range, and the signal quality stayed in the good category. Packet loss was low enough that any missing packet could be compensated for by the next transmission, given the 10 s update interval. A summary of the measured communication metrics is presented in Table IV.

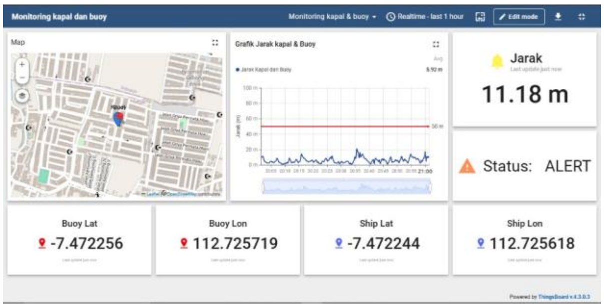
TABLE IV
SUMMARY OF SYSTEM PERFORMANCE UNDER BOTH TEST CONDITIONS

Metric	Without Obstacle	With Obstacle
Average GPS error	3.42 %	24.07 %
MAE	1.82 m	6.36 m
RMSE	2.47 m	6.93 m
Delay range	200-230 ms	210-230 ms
RSSI range	-56 to -98 dBm	-57 to -85 dBm
Packet loss range	0-10 %	0-10 %

The measured delay of 200–230 ms indicates that the proposed system is sufficiently responsive for early warning. The RSSI values, ranging from -56 dBm to -98 dBm in the open-area scenario and from -57 dBm to -85 dBm in the obstacle scenario, still fall within the good-to-very-good category according to the project criteria. Packet loss in the range of 0–10% does not significantly affect real-time monitoring, as telemetry is updated periodically. Overall, these results confirm that LoRa is a suitable communication medium for this low-power ship–buoy monitoring application.

D. Real-Time Visualization on ThingsBoard

One of the main outputs of the proposed system is real-time visualization through ThingsBoard. The dashboard displays the ship and buoy coordinates, the latest distance value, and the current safety status. When the calculated distance is 50 m or less, the status changes to ALERT; otherwise, it remains SAFE. This dashboard allows the operator to monitor the interaction between the two objects and respond more quickly when the ship enters the unsafe zone.



Jarak
11.18 m

Status: ALERT

Buoy Lat -7.472256

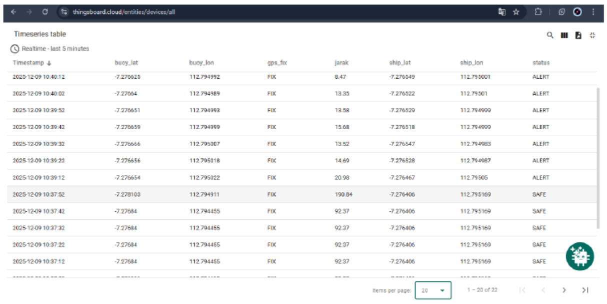
Buoy Lon 112.725719

Ship Lat -7.472244

Ship Lon 112.725618

Fig. 5. ThingsBoard dashboard used for real-time ship-buoy proximity monitoring

In addition to the dashboard widgets, buoy telemetry is also stored in a time-series table on ThingsBoard, as shown in Fig. 6. This view records the raw values of ship_lat, ship_lon, buoy_lat, buoy_lon, the computed distance, the safety status, and GPS fix information in chronological order. It is useful for validating the dashboard because each update can be checked directly at the telemetry level.



Timestamp ↓	buoy_lat	buoy_lon	gps_fix	jarak	ship_lat	ship_lon	status
2025-12-09 10:40:12	-7.276625	112.794992	FIX	8.47	-7.276549	112.795001	ALERT
2025-12-09 10:40:02	-7.27664	112.794989	FIX	13.35	-7.276522	112.79501	ALERT
2025-12-09 10:39:52	-7.276651	112.794993	FIX	13.58	-7.276529	112.794999	ALERT
2025-12-09 10:39:42	-7.276659	112.794999	FIX	15.68	-7.276518	112.794999	ALERT
2025-12-09 10:39:32	-7.276666	112.795007	FIX	13.52	-7.276547	112.794983	ALERT
2025-12-09 10:39:22	-7.276656	112.795018	FIX	14.60	-7.276528	112.794987	ALERT
2025-12-09 10:39:12	-7.276654	112.795022	FIX	20.98	-7.276467	112.79505	ALERT
2025-12-09 10:37:52	-7.278103	112.794911	FIX	190.84	-7.276406	112.795169	SAFE
2025-12-09 10:37:42	-7.27684	112.794455	FIX	92.37	-7.276406	112.795169	SAFE
2025-12-09 10:37:32	-7.27684	112.794455	FIX	92.37	-7.276406	112.795169	SAFE
2025-12-09 10:37:22	-7.27684	112.794455	FIX	92.37	-7.276406	112.795169	SAFE
2025-12-09 10:37:12	-7.27684	112.794455	FIX	92.37	-7.276406	112.795169	SAFE

Fig. 6. Time-series telemetry table on ThingsBoard

The time-series table confirms that the system updates data periodically and stores each telemetry sample sequentially. Consistent with the final project report, the status changes to ALERT when the distance is 50 m or less and returns to SAFE when the distance exceeds 50 m. This view strengthens the monitoring analysis by linking the dashboard's visual behavior to the underlying telemetry records.

V. Conclusion

This paper presents a GPS-based proximity detection system intended to improve safety in maritime navigation between a ship and a buoy. The proposed design integrates GPS Neo-6M modules, TTGO ESP32 LoRa boards, the Haversine formula, and ThingsBoard visualization into a complete monitoring framework. The buoy node serves as the central processing point, calculating distances locally and generating SAFE or ALERT decisions before forwarding the data to the gateway and dashboard.

Experimental results show that the system performs well in an open-area scenario, achieving an average distance error of 3.42%, an MAE of 1.82 m, and an RMSE of 2.47 m. When an obstacle is introduced, the distance error increases, but the system still provides meaningful monitoring information. LoRa communication remains stable, with normal delay, good RSSI, and low packet loss. Therefore, the proposed system can serve as a practical and affordable early-warning solution for small-vessel navigation. Future work should separate the gateway from the buoy node, apply filtering techniques to reduce GPS fluctuation, and validate the system in an actual maritime environment.

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