PROGRESS IN ENGINEERING APPLICATION AND TECHNOLOGY
e-ISSN: 2773-5303

PEAT

Vol. 6 No. 1 (2025) p. 462-470
https://publisher.uthm.edu.my/periodicals/index.php/peat

Solar Powered GPS Based Wild Animal Tracking System

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DOI: https://doi.org/10.30880/peat.2025.06.01.048

Article Info

Received: 17 January 2025
Accepted: 30 January 2025
Available online: 30 April 2025

Keywords

Animal Tracking, GPS Tracking, ESP32, Node-RED, Solar, Wildlife Tracking, IoT

Abstract

This project focuses on developing a solar-powered GPS-based system for tracking wild animals, aiming to provide a sustainable, efficient, and reliable solution for continuous wildlife monitoring. The system addresses challenges in existing tracking methods, such as limited battery life and the lack of real-time behavioral analysis, by integrating a GPS module and an accelerometer, powered by a solar panel, to ensure uninterrupted operation. Data collected is transmitted via MQTT to a cloud-based dashboard for remote monitoring and analysis. Experimental results indicate that the system provides accurate real-time tracking with an average positional error of 18 meters, while accelerometer-based motion analysis enhances behavioral observation by detecting movement patterns and potential signs of distress. The findings highlight the feasibility of leveraging renewable energy for long-term animal tracking, demonstrating significant improvements over conventional battery-powered devices. Future enhancements may include integrating LoRa communication for extended range and AI-based behavioral pattern analysis to refine data interpretation and improve conservation strategies.

1. Introduction

The encroachment of human civilization into wildlife habitats has led to increased human-animal conflicts, particularly in regions where urbanization and infrastructure development intersect with natural ecosystems. Highways, deforestation, and agricultural expansion fragment animal habitats, forcing wildlife to navigate human-dominated landscapes, often leading to fatal road accidents and habitat loss. Endangered species such as the Malayan Tiger and Malayan Tapir are especially vulnerable to these threats, necessitating innovative conservation solutions.

Current animal tracking methods, such as satellite collars and RFID-based systems, present challenges including limited battery life, high costs, and the need for frequent maintenance. While GPS-based tracking offers a viable alternative, the reliance on conventional battery-powered devices limits long-term deployment. To address this issue, integrating solar energy with IoT-enabled tracking systems presents a sustainable solution.

Previous research has demonstrated the effectiveness of GPS tracking in wildlife studies, particularly in monitoring migration patterns, habitat usage, and behavioral analysis. For instance, Schofield et al. (2007) successfully employed GPS tracking to study sea turtle migration, providing critical insights into their conservation needs [5]. Additionally, Ahmed et al. (2023) explored IoT-based LoRaWAN tracking systems, highlighting the advantages of low-power, long-range communication for real-time tracking in remote areas [9]. Other studies, such as those by Kadek Cahyati Arta (2022) and Jnana K.P (2022), have explored IoT-based tracking solutions for both wildlife and vehicle monitoring, demonstrating the practical applications of GPS and accelerometer integration in real-time data transmission [6][7]. The application of GPS tracking has also been extended to human tracking, as seen in Hamzah M. Marhoon's (2023) low-cost children tracker system, which relies on mobile GPS data for real-time monitoring [8].

The adoption of LoRaWAN-based tracking systems, such as the work by Abdelrahman Ahmed (2023), underscores the growing interest in energy-efficient and long-range communication for asset tracking, including wildlife monitoring [9]. In an outdoor connectivity study, Rendeiro et al. (2023) evaluated ESP32's WiFi performance, demonstrating its feasibility for medium-range IoT applications, which aligns with the current project's focus on wireless communication for animal tracking [10]. Additionally, military applications of IoT tracking, such as the system developed by Sujitha V (2022) for real-time health monitoring of soldiers, highlight the broader implications of integrated sensor technologies for tracking and monitoring purposes [15].

This project proposes the development of a solar-powered GPS-based animal tracking system to improve wildlife monitoring. By leveraging an ESP32 microcontroller, Neo-6M GPS module, and ADXL345 accelerometer, the system provides real-time movement tracking while ensuring energy efficiency through solar charging. The data collected is transmitted via MQTT to a cloud-based dashboard for remote monitoring and analysis. This approach aims to enhance conservation efforts, reduce human-wildlife conflicts, and provide a scalable tracking solution for long-term deployment in remote environments.

2. Methodology

This section gives a general summary of the technique used, including the actions needed to successfully design, develop, and execute the system. The methodology consists of many important phases, such as system flowchart and block diagram, where each is necessary for the successful completion of the project.

2.1 System Block Diagram

The solar-powered GPS-based animal tracking system is depicted in Figure 1 as a block diagram. This system utilizes solar energy and key components to efficiently track animal location and movements. A solar panel connected to a TP4056 charge module provides energy to the ESP32 microcontroller while simultaneously charging the battery, ensuring sustainable operation. At the core of the system, the ESP32 microcontroller manages data from the GPS module, which tracks the animal's location, and the ADXL345 accelerometer, which measures movement. Data is transmitted via an access point using an internet connection to an MQTT broker, which facilitates communication with Node-RED. Node-RED processes the data and provides a user-friendly interface for monitoring location and activity. This system integrates solar power, GPS tracking, and data visualization to deliver accurate and timely insights, aiding in monitoring animal behavior across various environments.

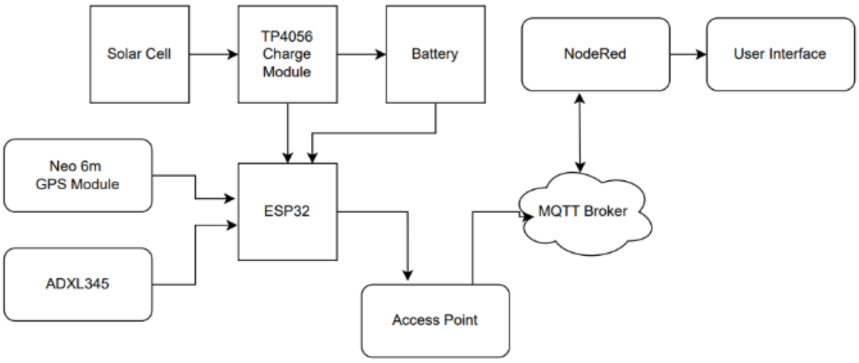


Fig. 1: System Block Diagram

2.2 System Flowchart

The system flowchart in Figure 2 visualizes the operational flow of an IoT-based wildlife tracking system designed to collect and process data from various sensors and transmit it for further handling and display. The system operates through interconnected phases, beginning with initialization, where parameters and configurations are set, including a counter variable. The system establishes a Wi-Fi connection, crucial for data transmission, and retries until successful if it fails. Once connected, GPS data is collected to determine location, followed by accelerometer data to assess movement and orientation. This data is processed and encoded for transmission to an MQTT broker, which distributes it to endpoints for further handling. Node-RED processes the received data using predefined workflows, preparing it for display. The final phase updates the user interface with real-time visual feedback, and the system rechecks Wi-Fi connectivity to ensure uninterrupted operation. This structured flow guarantees continuous and efficient data collection, processing, and visualization.

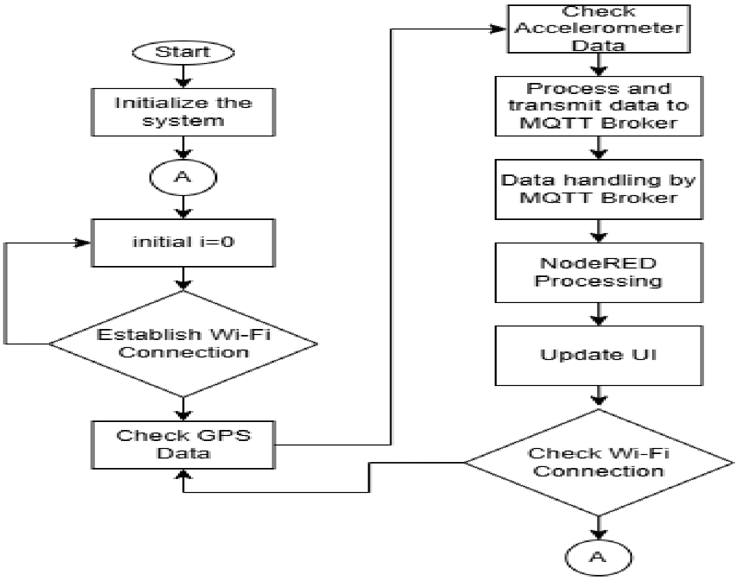
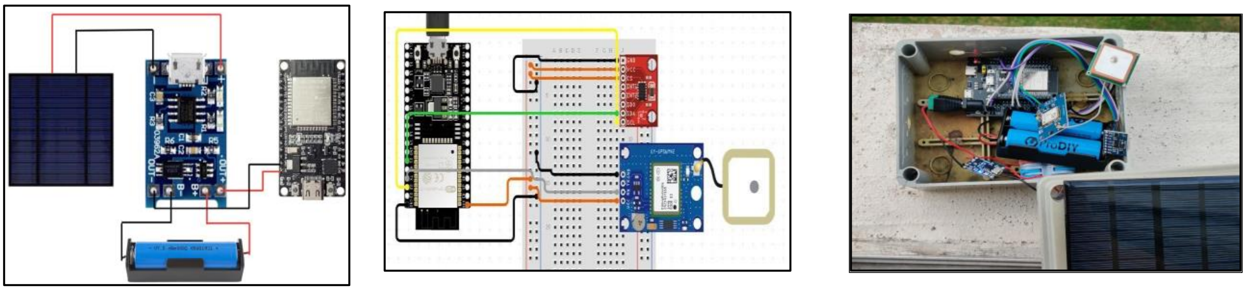


Fig. 2: System Flowchart

2.3 Circuit Diagram and Hardware Connection



(a) **(b)** **(c)**

Fig. 3: Circuit Diagram (a) Solar Panel Connection; (b) Sensor Connection; (c) Hardware Setup

The solar-powered IoT system's functionality is illustrated in Figures 3, (a) and (b), demonstrating the integration of solar power, GPS tracking, and motion sensing. The solar panel captures sunlight and sends the power to the TP4056 Charge Controller, which efficiently manages lithium battery charging to ensure safe energy storage. The battery powers the ESP32 microcontroller through the regulated output of the charge controller, enabling continuous operation. The GPS module, connected to the ESP32 microcontroller, determines the system's location by receiving satellite signals, while the accelerometer measures orientation and movement data. The ESP32 processes inputs from both the GPS module and the accelerometer, ensuring real-time data handling. By combining solar power, GPS tracking, and motion sensing, this project creates a self-sustaining IoT system capable of operating in remote areas without external power sources. The ESP32 microcontroller serves as the central processor, efficiently managing data, monitoring animal well-being, and optimizing power usage, making the system ideal for various remote monitoring and tracking tasks. Figure 3 (c) shows the completed hardware circuit

2.4 Data Processing Method

The data processing methods were designed to ensure accuracy and reliability using data from the GPS module, ADXL345 accelerometer, and battery monitoring system. Each sensor's raw data was processed using appropriate formulas and validation checks to track animal behavior and monitor system performance effectively.

2.4.1 GPS Coordinate

The GPS module, utilizing the TinyGPSPlus library, logged latitude and longitude values in real time. The system validated this data before publishing it to the MQTT broker. To analyze movement, the Haversine formula (Eq. 1) was used to calculate the displacement between two GPS points, considering differences in latitude (Δϕ) and longitude (Δλ) along with the Earth's radius (R). The Angular Distance formula (Eq. 2) determined the angular distance (c) between two points on a sphere. Finally, the Distance formula (Eq. 3) converted angular distance into a linear distance (d), providing precise movement patterns. These calculations ensured accurate geolocation and navigation data essential for tracking.

2.4.2 Acceleration

The The ADXL345 accelerometer measured acceleration along the X, Y, and Z axes. The raw data was scaled using a sensitivity factor of 256 LSB/g for ±2g to calculate acceleration (ax,ay,az) using Eq. 4. To determine orientation, pitch and roll angles were calculated using Eq. 5 and Eq. 6, where the angles depended on acceleration values relative to gravity (9.8 ms−2). Thresholds were set at 70° for pitch and roll over five consecutive readings to detect events like falls, providing insights into the animal's behavior.

2.4.3 Battery Monitoring

The battery voltage, monitored through analog pin, was converted into percentage using Eq. 7. This formula used VmeasuredV_{measured}Vmeasured (measured voltage), VminV_{min}Vmin (minimum operating voltage of 3.0V), and VmaxV_{max}Vmax (maximum voltage of 4.2V) to calculate the battery's remaining charge. This data, sent to the MQTT broker, allowed remote monitoring to prevent unexpected system shutdowns. Through these processing methods and equations, the system ensured precise, validated data for real-time tracking and monitoring, making it robust and reliable for its intended application.

$$hav\theta \; or \; a = \sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos(\varphi 1) \; . \cos(\varphi 2) \; . \sin^2\left(\frac{\Delta\lambda}{2}\right) \tag{Eq1}$$

$$c = 2 \; . \; arctan \; 2 \; (\sqrt{a}, \sqrt{1-a}\,) \tag{Eq2}$$

$$d = R \; . \; c \tag{Eq3}$$

$$a = raw \; data \; x \; \frac{gravity}{sensitivity \; scale \; factor} \tag{Eq4}$$

$$Pitch = \arctan\left(\frac{a_y}{\sqrt{a_x^2 + a_z^2}}\right) . \frac{180}{\pi} \tag{Eq5}$$

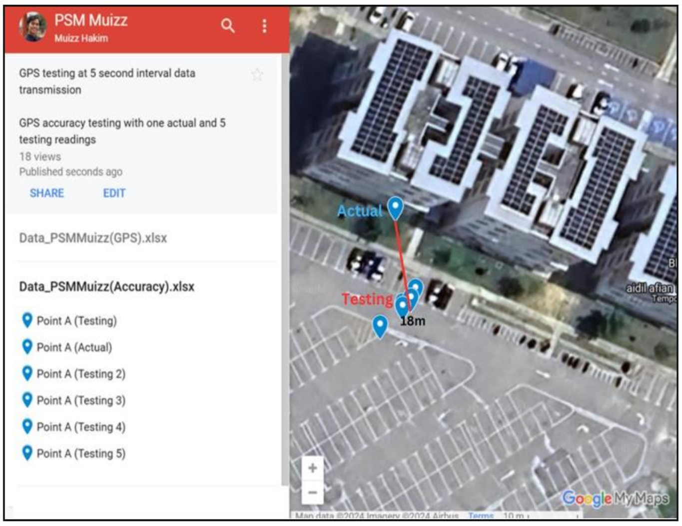
$$Roll = arctan\left(\frac{a_x}{\sqrt{a_y^2 + a_z^2}}\right) . \frac{180}{\pi} \tag{Eq6}$$

$$Battery \; Percentage = \frac{V_{measured} - V_{min}}{V_{max} - V_{min}} \; x \; 100 \tag{Eq7}$$

3. Result & Discussion

This section presents the results of a solar-powered IoT-based wildlife tracking system. Extensive testing confirmed the system's reliability, with real-time data collection and visualization achieved via Node-RED and MQTT. The system operated continuously on solar power and demonstrated accurate GPS and accelerometer data analysis. Results are summarized through tables, graphs, and dashboards, showcasing its effectiveness in wildlife tracking.

3.1 GPS Tracking Accuracy



GPS testing at 5 second interval data transmission

GPS accuracy testing with one actual and 5 testing readings

18 views

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Data_PSMMuizz(Accuracy).xlsx

- Point A (Testing)
- Point A (Actual)
- Point A (Testing 2)
- Point A (Testing 3)
- Point A (Testing 4)
- Point A (Testing 5)

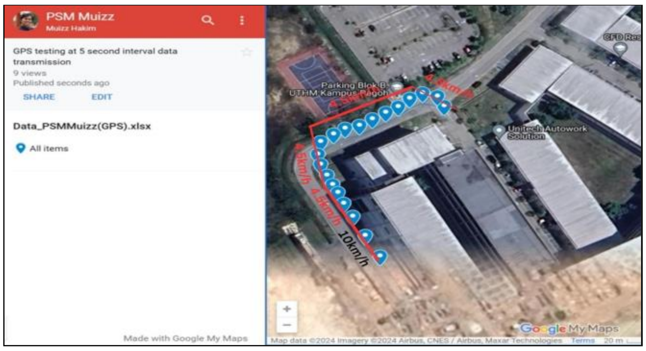
***Fig. 4*: Google Maps Visualization**

***Table 1*:** Sample of GPS data collection for accuracy evaluation

Timestamp	Latitude	Longitude	Distance from actual (m)
23-12-2024 16:52:41	2.144587	102.727982	17
23-12-2024 16:52:46	2.144609	102.728004	15
23-12-2024 16:52:51	2.144594	102.727997	17
23-12-2024 16:52:56	2.144581	102.727982	18
23-12-2024 16:53:01	2.144550	102.727943	22

The GPS tracking accuracy was assessed using the Neo-6M GPS module, which updated location data every five seconds in a semi-urban environment. The average positional error was 18 meters, with the best accuracy at 15 meters. Errors resulted from factors like multipath effects and poor satellite visibility but remained stable and sufficient for tracking in open and semi-open areas. Sample data and visualizations in Table 1 and Figure 4 illustrate the system's performance.

3.2 GPS Tracking Simulation Setup and Assumptions



GPS testing at 5 second interval data transmission

9 views

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Data_PSMMuizz(GPS).xlsx

- All items

***Fig. 5*: Google Maps Visualization**

Table 2: GPS Data collected in a Simulation

Timestamp	Latitude	Longitude	Direction	Heading (°)
16-12-2024 13:23:52	2.149880	102.729520	-	-
16-12-2024 13:23:57	2.149930	102.729495	NW	333.5°
16-12-2024 13:24:02	2.149946	102.729440	W	286.2°
16-12-2024 13:24:07	2.149919	102.729392	SW	240.6°
16-12-2024 13:24:12	2.149879	102.729348	SW	227.7°

A study in a controlled setting used GPS tracking to simulate wildlife movement patterns, replicating speeds typical of elephants, Malayan tigers, and goats. A human participant mimicked these movements at speeds ranging from 4.5 km/h to 10 km/h, simulating natural conditions with periods of sustained movement and rapid acceleration. The simulation, conducted around UTHM (Figure 5), logged GPS data every five seconds, capturing latitude, longitude, timestamp, direction, and heading (Table 2). The test began with walking at 4.5 km/h and transitioned to running at 10 km/h during the final 15 seconds. This setup effectively validated GPS tracking accuracy under conditions resembling real-life animal monitoring scenarios.

3.3 Behavioural Monitoring

Table 3: Orientation data of normal and flagged conditions

Timestamp	Pitch	Roll	Status
25-12-2024 20:42:29	-72.40°	9.40°	Normal
25-12-2024 20:42:34	-74.25°	7.33°	Normal
25-12-2024 20:42:39	-74.88°	6.43°	Normal
25-12-2024 20:42:44	-74.84°	6.18°	Normal
25-12-2024 20:42:49	-74.69°	6.42°	Animal is injured/dead
25-12-2024 20:42:54	-74.46°	6.61°	Animal is injured/dead

Behavioral monitoring used the ADXL345 accelerometer to record pitch and roll angles every five seconds, detecting abnormal movements indicating injury or death as shown in Table 3. Tilt angles exceeding 70° in pitch or roll for five consecutive readings triggered alerts for potential falls or injuries, such as a pitch of 80.5° and roll of 25.1°. This system efficiently differentiated routine movements from critical issues, enabling quick responses.

3.4 Battery Performance

Table 4: Battery discharge performance

Timestamp	Voltage	Percentage
24-12-24 15:05	4.10	95
24-12-24 15:10	4.07	92
24-12-24 15:15	4.04	89
24-12-24 15:20	4.01	86
24-12-24 15:25	3.98	83
24-12-24 15:30	3.95	80
24-12-24 15:35	3.92	77
24-12-24 15:40	3.89	74
24-12-24 15:45	3.86	71

24-12-24 15:50	3.83	68
24-12-24 15:55	3.80	65
24-12-24 16:00	3.77	62
24-12-24 16:05	3.74	59

Table 5: Battery charging performance

Timestamp	Voltage	Performance
30-12-24 09:00	3.85	40
30-12-24 10:00	3.92	50
30-12-24 11:00	4.00	65
30-12-24 12:00	4.10	85
30-12-24 13:00	4.15	95
30-12-24 14:00	4.20	100

The system utilizes two 18650 lithium-ion batteries rated at 6800mAh and 3.7V each, connected in parallel to double the total capacity, ensuring extended operation. A TP4056 charge module manages solar charging and supplies power to the ESP32 microcontroller, maintaining efficient power management for continuous operation in remote environments. Battery voltage during charge and discharge cycles ranged from 3.0V to 4.2V, with an average consumption of 1% per hour as the system transmitted data and maintained Wi-Fi connectivity every five seconds.

Over a 60-minute observation period without entering deep sleep mode, battery performance showed a steady decline, reflecting consistent power demands from the GPS, accelerometer, and microcontroller. The data, as shown in Table 4, highlights three distinct phases of discharge. In the initial phase (0–20 minutes), voltage decreased from 4.10V to 3.95V (95% to 75%), indicating stable early operation. The middle phase (20–40 minutes) saw a gradual decline from 3.95V to 3.83V (75% to 65%), demonstrating consistent discharge as power demands remained steady. In the final phase (40–60 minutes), voltage dropped to 3.74V (59%), nearing the lower operational range but maintaining reliability.

During daylight hours, the solar panel delivered a variable charging current based on sunlight intensity, with optimal conditions yielding a charging rate of approximately 300–350mA. Over the course of an 8–10 hour charging cycle, the TP4056 lithium-ion charge controller regulated the incoming power from the 5V 380mA solar panel, ensuring safe and efficient charging of the two parallel-connected 18650 lithium-ion batteries (3.7V, 13,600mAh total capacity). The charging voltage ranged between 4.0V and 4.2V, with the TP4056 automatically terminating the charge upon reaching full capacity to prevent overcharging.

Table 5 highlights three distinct phases of the charging process. In the initial phase (9:00–11:00), voltage increased from 3.85V to 4.00V (40% to 65%), indicating a steady power intake. The middle phase (11:00–12:00) saw a rapid increase from 4.00V to 4.10V (65% to 85%), reflecting peak solar efficiency. In the final phase (12:00–14:00), voltage rose gradually from 4.10V to 4.20V (85% to 100%), with the TP4056 ensuring controlled saturation and charge termination. This regulation optimizes battery longevity while maintaining reliable power for the tracking system.

These results validate the system’s ability to operate efficiently under continuous use, with predictable and steady battery performance, making it suitable for long-term deployment in remote environments..

3.5 Data Transmission and Storage

A	B	C	D	E	F	G	H
Latitude	Longitude	Pitch	Roll	Voltage	Battery Percenta	Speed	Direction
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.09	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:-14.41	roll:7.63	voltage:0	battery_percenta	speed:0.09	direction:"Unknown"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.87	direction:"East"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.87	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:-14.62	roll:7.62	voltage:0	battery_percenta	speed:0.87	direction:"Unknown"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.2	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.2	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:-14.62	roll:7.62	voltage:0	battery_percenta	speed:0.2	direction:"Unknown"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.37	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.37	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:-14.41	roll:7.63	voltage:0	battery_percenta	speed:0.37	direction:"Unknown"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.24	direction:"West"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.24	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:-14.3	roll:7.36	voltage:0	battery_percenta	speed:0.24	direction:"Unknown"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.07	direction:"West"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.07	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:-14.62	roll:7.41	voltage:0	battery_percenta	speed:0.07	direction:"Unknown"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.24	direction:"Southwest"}
{"latitude":2.144	longitude:102.72	pitch:0	roll:0	voltage:0	battery_percenta	speed:0.24	direction:"North"}
{"latitude":2.144	longitude:102.72	pitch:-14.41	roll:7.42	voltage:0	battery_percenta	speed:0.24	direction:"Unknown"}

Speed (km/h) 2 km/h

Orientation -180 °

Battery 50

Direction Unknown

(a) (b)

***Fig. 6*: Data Uploaded to Excel using MQTT Protocol (a); Node-RED Dashboard (b)**

The system transmits GPS coordinates, orientation data, and battery percentage to the Node-RED database and dashboard via the MQTT protocol, providing real-time updates in a user-friendly interface as shown in Figure 6 (b). Simultaneously, the data is exported to Excel for localized storage, enabling cross-checking and preventing data loss as shown in Figure 6 (a). Accurate calculations and validation mechanisms ensure the data's precision and reliability, making the system highly functional and suitable for its intended purpose.

4. Future Improvements

An organized and precise methodology was applied in developing a solar-powered, IoT-enabled GPS-based animal tracking system to ensure dependable and efficient operation. The project successfully integrated hardware and software components, including the ESP32 microcontroller, Neo-6M GPS module, and ADXL345 accelerometer, to monitor animal movements and behaviors. Real-time data transmission and visualization using Node-RED provide user-friendly access to location and behavioral insights, meeting all project objectives. The system demonstrated sustainability through its solar-powered design and proved reliable under testing, showing great potential for wildlife conservation and public safety applications.

Future improvements could include integrating advanced sensors to enhance accuracy, adopting LoRa technology for wider and more robust coverage, and incorporating a camera for visual monitoring. Transitioning from Node-RED to a custom-built application could also improve flexibility and reliability, tailoring the software to specific user needs. With these enhancements, the system's relevance and capabilities in the evolving field of IoT-enabled wildlife tracking can be further solidified.

5. Conclusion

This study successfully developed a solar-powered GPS tracking system that enhances wildlife conservation efforts by offering real-time monitoring and behavioral insights. Future work may involve integrating LoRa communication for extended range and AI-based behavioral pattern analysis.

Acknowledgement

The author would like to thank the Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia for providing support along the way of completing the project paper.

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