

Geofencing Based Pet Tracking and Protection System

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Abstract - Pet safety and real-time location monitoring have become paramount in urban and semi-urban environments where domesticated animals face continuous risks of accidental wandering, loss, or theft. Traditional containment mechanisms, such as physical leashes and static fences, impose significant mobility restrictions, while passive identification tags provide no active tracking or preventative alerting capabilities. This paper presents a comprehensive design and implementation of a low-cost, collar-mounted IoT pet tracking and geofencing system. The embedded hardware architecture integrates an ESP32 microcontroller with a NEO-6M GPS receiver for precise position extraction and a SIM800L GPRS cellular module for wide-area wireless connectivity. To resolve the intrinsic lack of Transport Layer Security (TLS) support on low-cost 2G cellular modems, the system incorporates a server-side Node.js MQTT-to-Firebase bridge that securely relays telemetry data to the Firebase Realtime Database. A cross-platform Flutter mobile application serves as the primary user interface, enabling pet owners to visualize live locations, review historical movement trails, monitor system telemetry, and receive instant boundary breach notifications. Rule-based geofencing is executed locally on the collar and cloud-side using the Haversine formula to compute great-circle distances between the device coordinates and the predefined safe-zone center. Experimental evaluations validate the feasibility, cost-effectiveness, and operational reliability of this architecture for real-time pet protection.

Key Words: Pet tracking, Geofencing, Internet of Things (IoT), ESP32, GPS, MQTT, Firebase, Mobile application.

1. INTRODUCTION

The ownership of domestic pets entails a significant responsibility toward ensuring their safety, health, and security. In densely populated urban settings and sprawling suburban neighborhoods, wandering pets are highly susceptible to becoming lost, encountering traffic hazards, or falling victim to theft [2]. Conventional containment methods, including physical boundaries, fenced yards, and standard collars with engraved identification tags, are fundamentally reactive or restrictive [2]. They fail to provide continuous, active surveillance or immediate notification when an animal breaches a designated safe boundary.

To overcome these limitations, modern technological advancements in the Internet of Things (IoT), satellite navigation, and wireless cellular networks have enabled the development of intelligent wearable tracking devices [2]. However, many commercial solutions and existing academic prototypes suffer from prohibitive hardware costs, excessive power consumption, or reliance on complex cloud dependencies that limit accessibility for average pet owners [2].

This work addresses these challenges by introducing an affordable, real-time pet tracking and geofencing system that couples lightweight hardware with robust cloud integration [1]. The main contributions of this work include:

- A low-cost hardware architecture utilizing an ESP32 microcontroller, NEO-6M GPS, and SIM800L GPRS module.
- A server-side Node.js bridge that resolves the TLS compatibility limitation of the SIM800L modem by bridging plain TCP MQTT to Firebase Realtime Database.
- Bidirectional geofence synchronization between the mobile application and the wearable collar.
- A scalable database model supporting multiple collars and historical tracking.

2. RELATED WORK AND LITERATURE REVIEW

The domain of geofencing and IoT-based animal monitoring has been widely explored in recent academic literature. Kothari et al. [1] demonstrated vehicle and asset tracking architectures utilizing GPS and GSM modules, establishing that rule-based geofencing computations without complex machine learning overhead are highly effective for reliable boundary alert generation. Similarly, Setiawan et al. [4] implemented an Arduino and Android-based pet tracking system using a NEO-6M GPS sensor and a SIM800L cellular module, demonstrating the viability of low-cost components for consumer-level tracking. Pangestu et al. [6] investigated mobile-side geofencing evaluation frameworks to offload computational tasks from wearable hardware. Furthermore, recent studies focusing on IoT animal collars emphasize the utility of low-power microcontrollers such as the ESP32 paired with cellular communication protocols to ensure reliable connectivity across diverse geographical terrains. While prior works validate

individual hardware components, integrating secure cloud relay bridges for legacy 2G modems while maintaining real-time mobile application synchronization remains an area requiring streamlined architectural design. Additional foundational studies in vehicle tracking and asset localization provide conceptual parallels for geofence boundary enforcement and remote telemetry streaming.

3. RESEARCH GAP AND OBJECTIVES

A thorough analysis of existing literature reveals several prominent technical gaps: high power consumption resulting from continuous, unoptimized GPS polling; excessive hardware costs that restrict widespread consumer adoption; and a scarcity of explicitly documented, non-machine-learning pet-tracking frameworks optimized for low-power microcontrollers. Many commercial modems lack native security protocols required for direct cloud ingestion, creating integration bottlenecks. This work directly addresses these gaps by establishing a lightweight ESP32-based smart collar that performs efficient local distance calculations and transmits compact telemetry payloads via MQTT. The core objectives of the proposed system are:

- To design an affordable, wearable IoT collar capable of continuous GPS data acquisition and cellular transmission.
- To implement a secure server-side bridge that successfully bypasses the TLS limitations of low-cost GPRS modules.
- To develop a reliable rule-based geofencing mechanism utilizing the Haversine formula for accurate boundary monitoring.
- To provide a feature-rich Flutter mobile application for real-time tracking, historical trail visualization, and instant alert management.

4. PROPOSED SYSTEM AND ARCHITECTURE

The proposed system architecture is engineered to establish seamless, low-latency communication between the physical wearable collar, backend cloud infrastructure, and the end-user mobile application [1]. The end-to-end data flow operates across distinct modular tiers: location data is captured by the onboard GPS receiver, processed by the microcontroller, and transmitted over GPRS via MQTT protocol to an intermediate server bridge, which subsequently synchronizes with the cloud database for client-side rendering [1].

The structured data transmission pipeline is represented as:

ESP32 + NEO-6M + SIM800L → MQTT Broker (via GPRS)
→ Node.js Bridge → Firebase → Flutter App (1)

Conversely, the return communication path enables dynamic geofence configuration updates initiated from the mobile application. These parameters propagate through the cloud database, traverse the Node.js bridge, and are published via MQTT down to the ESP32 collar, ensuring real-time bidirectional synchronization [1].

5. SYSTEM DESIGN AND METHODOLOGY

5.1 Haversine Distance Calculation

To determine whether a monitored pet has breached a designated safe perimeter, the wearable collar computes the great-circle distance d between its current geographic coordinates (φ_1, λ_1) and the pre-configured geofence center coordinates (φ_2, λ_2) [1], [3]. This spatial evaluation utilizes the Haversine formula, which accounts for the spherical curvature of the Earth:

$$a = \sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos\varphi_1 \cos\varphi_2 \sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (2)$$

$$d = 2R \cdot \arcsin(\sqrt{a}) \quad (3)$$

where a is the intermediate haversine term, $R = 6,371$ km represents the mean radius of the Earth, $\Delta\varphi = \varphi_2 - \varphi_1$ denotes the latitude difference, and $\Delta\lambda = \lambda_2 - \lambda_1$ denotes the longitude difference, with all angles expressed in radians [1]. The pet is verified to be safely inside the permitted boundary if the computed distance satisfies the condition $d \leq r$, where r represents the user-defined geofence radius [1]. If $d > r$, an immediate boundary breach condition is flagged and transmitted to the cloud [1].

5.2 Telemetry and Communication Workflow

The ESP32 firmware executes a scheduled operational loop where telemetry data packets are compiled into standardized JSON formats [1]. These payloads encapsulate essential operational parameters, including current latitude, longitude, computed distance from the safe-zone center, boundary status flags, and onboard battery voltage levels [1]. Telemetry publishing occurs at fixed intervals (e.g., every 5 seconds) to balance tracking granularity with power conservation [1].

6. HARDWARE AND SOFTWARE IMPLEMENTATION

The physical prototype integrates modular electronic components housed within a lightweight, ergonomic, and durable collar enclosure suitable for daily animal wear [1]. Table 1 outlines the primary hardware specifications, designated system roles, and communication interfaces utilized in the prototype.

Table -1: Hardware Component Specifications

Component	Role	Interface
ESP32 Dev Module	Central Controller & Geofence Logic	–
NEO-6M GPS	NMEA Position Extraction	UART2 (9600 baud)
SIM800L GPRS	Cellular Connectivity	UART1 (9600 baud)

The embedded firmware is written in C++ within the Arduino development ecosystem [1]. It integrates robust open-source libraries, including TinyGPSPlus for parsing NMEA data streams from the GPS module, TinyGSM for AT-command modem communication, and PubSubClient for lightweight MQTT message publishing and subscription [1]. The backend synchronization bridge is developed in Node.js, while the cross-platform mobile user interface is engineered using the Flutter framework [1].

7. EXPERIMENTAL SETUP AND RESULTS

Rigorous testing was conducted under real-world field conditions to evaluate system responsiveness, cellular connection stability, and end-to-end telemetry flow. Live position updates, calculated distance metrics, and boundary status flags were successfully verified in real-time within the Firebase console, while historical database nodes accurately accumulated movement trails. Quantitative metrics such as exact battery drain profiles and precise GPS error margins under dense urban cover remain subject to ongoing multi-environment optimization.

8. CHALLENGES, LIMITATIONS, AND DISCUSSION

Several technical challenges were encountered during the development lifecycle. Most notably, the SIM800L cellular module lacks native hardware support for modern Transport Layer Security (TLS) encryption, preventing direct, secure TCP connections to contemporary cloud databases. This constraint was successfully resolved by deploying an intermediate Node.js MQTT bridge that acts as a secure intermediary. Additional practical limitations include cellular signal attenuation in remote rural areas impacting GPRS stability, GPS signal multipath reflection and drift affecting tight geofence boundaries (such as radii under 10 m), and operational volatility inherent in public MQTT broker instances.

9. FUTURE ENHANCEMENTS

Future iterations of the platform will focus on several architectural and hardware upgrades to improve reliability and scalability. Planned enhancements include transitioning to an LTE Cat-1 cellular module equipped with native TLS support (such as the SIM7600 or A7670

series) to eliminate the dependency on external server bridges, containerizing and deploying the backend bridge on a scalable cloud container service provider, implementing geofence hysteresis algorithms to prevent boundary-flipping notification chatter along perimeter edges, and integrating over-the-air (OTA) firmware update capabilities.

10. CONCLUSIONS

This paper presented the complete design, development, and evaluation of a low-cost IoT-based pet tracking and geofencing system. By integrating an ESP32 microcontroller, satellite GPS positioning, and a lightweight MQTT-to-Firebase bridge, the architecture successfully bypasses the hardware security constraints of low-cost cellular modems while delivering reliable, real-time monitoring capabilities through a responsive Flutter mobile application. Field testing confirms that the proposed system offers an accessible, practical, and effective solution for modern pet safety and perimeter security.

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