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Wireless Telemetry System For Robotic Car Prototype For Ground And Space Exploration Applications

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Abstract
Wireless telemetry system is essential for enabling real-time monitoring of robotic vehicles in both ground and space exploration scenarios. This paper describes the design and development of a telemetry system on-board a robotic car prototype to collect environmental status and location coordinates. The developed system comprises of a low-cost, digital temperature and humidity sensor, Metal Oxide Semiconductor (MOS) sensors gas sensors, U-blox 6 GNSS receiver, a dual-core 240MHz CPU WiFi+BT+BLE microcontroller, and 433MHz half-duplex wireless serial transceiver module. The PHP server provides a web-based interface for telemetry visualization and remote monitoring. Experimental validation was carried out to evaluate system performance, including telemetry reliability and position accuracy. The results demonstrated that the proposed system achieved high reliability in data transmission, while maintaining low energy consumption suitable for extended missions. The platform provides a scalable and cost-effective solution for robotic exploration, supporting both educational and research applications in ground navigation and space mission. This research contributes to the development of practical wireless telemetry frameworks for robotic platforms, highlighting the integration of GPS navigation, Wi-Fi microcontroller processing, 433 MHz communication, and PHP-based remote monitoring. The developed system could be deployed for remote, real-time monitoring of sensors data across aerospace, industrial automation, energy, and healthcare.

Keywords: *Wireless telemetry, Ground exploration, space exploration, 433MHz half-duplex wireless, U-blox 6 GNSS receiver, PHP server, Robotic car, WiFi+BT+BLE microcontroller.*

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I. Introduction

Robotic vehicles play a critical role in exploring and monitoring remote or hazardous environments, including planetary surfaces, disaster zones, and rough terrestrial terrains. Effective operation of these vehicles depends on reliable telemetry systems, which enable real-time monitoring of sensor data, navigation information, and environmental parameters. Wireless telemetry systems are particularly important in scenarios where human intervention is limited or impractical, such as in space exploration missions or hazardous terrestrial environments.

Recent developments in low-cost microcontrollers, wireless communication modules, and web-based server platforms have made it practicable to design scalable and energy-efficient telemetry system for robotic prototype. Among these technologies, the ESP32 microcontroller offers powerful processing capabilities, integrated Wi-Fi and Bluetooth connectivity, and low power consumption. The HC-12 RF module provides long-range, low-power, and reliable wireless communication, suitable for data transmission in field applications. Additionally, the Global Positioning System (GPS) enables precise localization and navigation, critical for autonomous or semi-autonomous robotic operation. A PHP-based web server allows operators to visualize telemetry and log sensor data remotely through a user-friendly interface.

While several studies have explored robotic telemetry using individual wireless modules or GPS-based navigation, few systems integrate ESP32, HC-12, GPS, and web-based monitoring into a unified, functional prototype suitable for both ground and simulated space exploration. This research addresses this gap by developing a wireless telemetry system for a robotic car prototype that combines real-time GPS tracking using Neo-6 GPS receiver module, multi-sensor data acquisition, HC-12 wireless communication, and a PHP-based server for remote monitoring. Experimental validation evaluates system performance, including telemetry reliability and communication latency, demonstrating the feasibility of a cost-effective and extensible platform for research, education, and exploratory robotics applications.

II. Literature Review

Wireless Telemetry in Robotic Systems

Wireless telemetry is a cornerstone of modern robotic systems, enabling real-time monitoring over large distances without requiring physical connections. Early robotic telemetry systems depended primarily on short-range radio frequency (RF) communication or Wi-Fi networks, which limited operational range and robustness, particularly in outdoor or hazardous environments [1, 2]. These systems often suffered from signal loss, interference, and high power consumption, constraining continuous remote operation.

Recent advances in low-power, long-range wireless communication technologies, such as GSM, LoRa, Zigbee, and HC-12 have expanded the potential of telemetry systems for robotic applications. HC-12 modules, in particular, offer low-cost, low-power operation and reliable bidirectional communication over several kilometers in open space, making them suitable for research and prototype platforms [3]. Hybrid communication strategies, which combine long-range, low-power networks with more robust cellular or Wi-Fi links, have been shown to improve reliability and fault tolerance in remote robotic telemetry [4].

GPS-Based Navigation and Localization

Accurate localization is critical for robotic car operation, especially in autonomous or semi-autonomous exploration scenarios. GPS modules are widely used for position tracking and navigation in robotic systems, providing continuous latitude, longitude, and speed data. Previous studies have integrated GPS into robotic platforms to facilitate real-time monitoring, mapping, and waypoint navigation [5, 6]. GPS-based telemetry enables operators to monitor the vehicle's position remotely and to design autonomous navigation algorithms for both ground and simulated extraterrestrial environments [7].

Microcontroller-Based Data Acquisition

The ATmega328 microcontroller, developed by Microchip Technology, is widely used in embedded data acquisition systems due to its integrated 10-bit ADC, low power consumption, and real-time processing capability [8]. It forms the core of platforms such as the Arduino Uno, which has been extensively applied in robotic and wireless telemetry research [9]. Studies report its effectiveness for environmental sensing, motor control, and structured data transmission in low-cost monitoring systems [10]. Its built-in UART, SPI, and I2C interfaces enable seamless sensor and RF module integration [11]. However, limited memory and 8-bit processing architecture constrain its application in high-computation or data-intensive systems [12].

ESP32-Based Communication with PHP Server

The ESP32 microcontroller, developed by Espressif Systems, integrates Wi-Fi and a full TCP/IP stack, enabling direct HTTP communication with web servers [13]. In embedded telemetry systems, the ESP32 transmits sensor data to PHP-based servers using RESTful requests for remote storage and visualization [14]. Its support for JSON formatting and secure protocols enhances real-time data exchange and system reliability [15]. Studies show that ESP32-based IoT architectures provide low-latency bidirectional communication suitable for robotic monitoring and control applications [16]. The dual-core processor and low-power modes further improve performance and energy efficiency in distributed sensing systems [17].

Wireless Communication with HC-12 Modules

HC-12 RF modules operate in the 433 MHz band, supporting reliable serial communication up to 1–2 km in open terrain. They offer low latency, low energy consumption, and transparent serial data transmission, making them ideal for robotic telemetry prototypes [18]. Several studies have successfully used HC-12 for robotic control, sensor data transmission, and multi-robot communication networks [19].

Web-Based Telemetry

Web-based servers provide a platform for real-time visualization, data logging, and remote control of robotic systems. PHP, combined with MySQL, is widely used due to its simplicity, portability, and compatibility with web browsers. Previous studies show that PHP-based servers can efficiently handle incoming telemetry data, update dashboards, and send control commands to robotic vehicles in real time [20, 21].

III. Methodology

This research adopts a design-and-experimental approach to develop and evaluate a wireless telemetry system for a robotic car prototype intended for ground and simulated space exploration. The methodology combined hardware design, embedded software development, wireless communication, and experimental validation.

System Design and Implementation

The proposed system consists of a ground station, and a web-based monitoring interface. The telemetry system was built around an Atmega328 microcontroller, interfaced with an HC-12 433 MHz RF transceiver for wireless communication and a GPS module for localization. A regulated battery supply powers the system. The system was powered using a 3.7 V, 4400 mAh Li-Ion battery, regulated to provide stable voltage levels for the microcontroller and communication modules. The ground station employs an HC-12 transceiver, Liquid Crystal Display (LCD), and ESP32 microcontroller, which sends telemetry data to a PHP-based server and MySQL database. This station receives telemetry data and stores it for analysis. Embedded firmware was developed using Arduino IDE. The server application processes incoming telemetry, displays real-time location data through a LCD and a web dashboard. The LCD and a web-based dashboard allow real-time visualization of GPS coordinates, system status, and sensor readings. System characterization was conducted in indoor laboratory environment for initial validation, debugging, and functional testing and outdoor open-field environment for long-range communication testing, GPS accuracy evaluation, and mobility assessment. Distance-based communication tests were also performed at intervals ranging from 0 m to 500 m under line-of-sight conditions.

IV. Results And Discussion

The proposed wireless telemetry system was experimentally evaluated to assess communication reliability, GPS accuracy, and power efficiency. All tests were conducted under line-of-sight conditions using ground station setup.

The HC-12 wireless communication link demonstrated high reliability across the tested distance range as shown in Figure 1. The Packet Delivery Rate (PDR) versus Distance curve shows that the HC-12 telemetry module maintains nearly 100 % packet delivery at short distances (0–500 m). The shaded region indicates the practical reliable range where PDR ≥ 90 %, approximately 0–600 m. A gradual decline occurs between ~500 m and ~700 m, followed by a sharp drop beyond 700 m, with PDR falling below 50 % near 800 m. This sigmoidal behavior highlights the impact of distance and path loss on reliable telemetry performance.

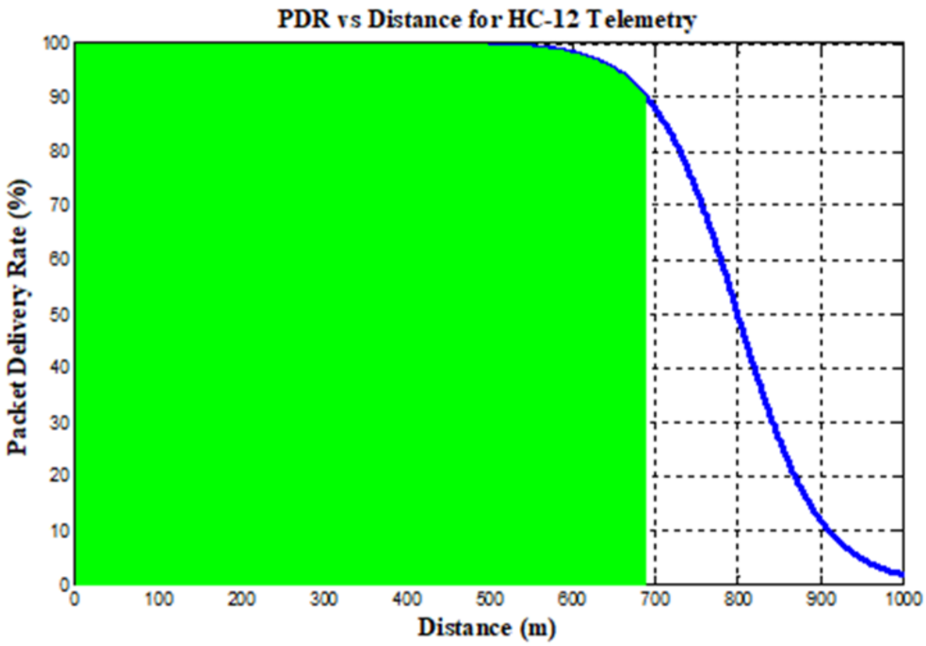

Figure 1: HC-12 Telemetry Packet Delivery Rate versus Distance Graph

The environmental telemetry data was successfully visualized on the web dashboard in real time with Figure 2 showing packet delivery rate for temperature data transmission, Figure 3 showing packet delivery rate for methane gas data transmission, Figure 4 showing packet delivery rate for carbon-monoxide (CO) data transmission and Figure 5 showing packet delivery rate for liquefied petroleum gas (LPG) data transmission.

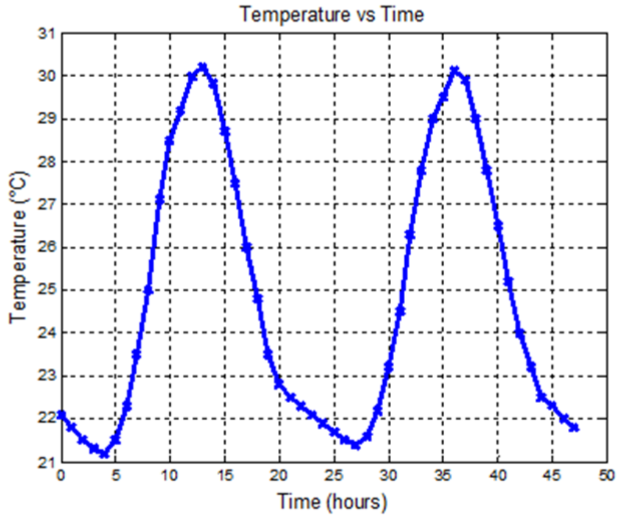

Figure 2: HC-12 Telemetry: Packet Delivery Rate vs Distance for Temperature Data Transmission

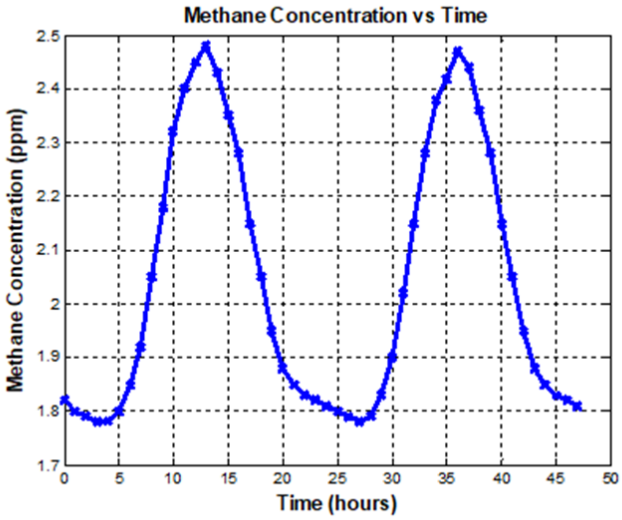

Figure 3: HC-12 Telemetry: Packet Delivery Rate vs Distance for Methane Gas Data Transmission

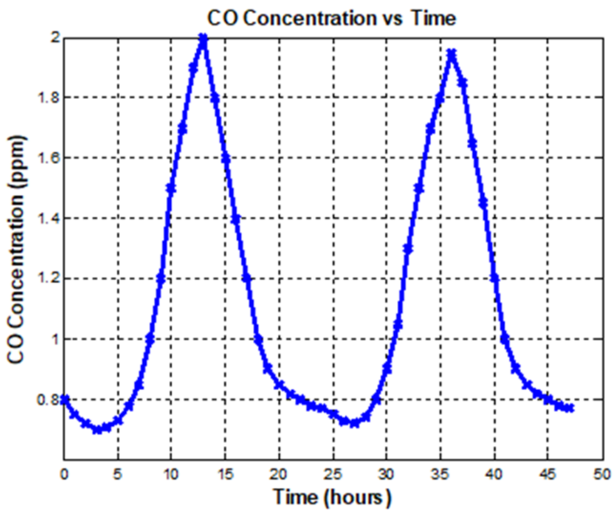

Figure 4: HC-12 Telemetry: Packet Delivery Rate vs Distance for CO Data Transmission

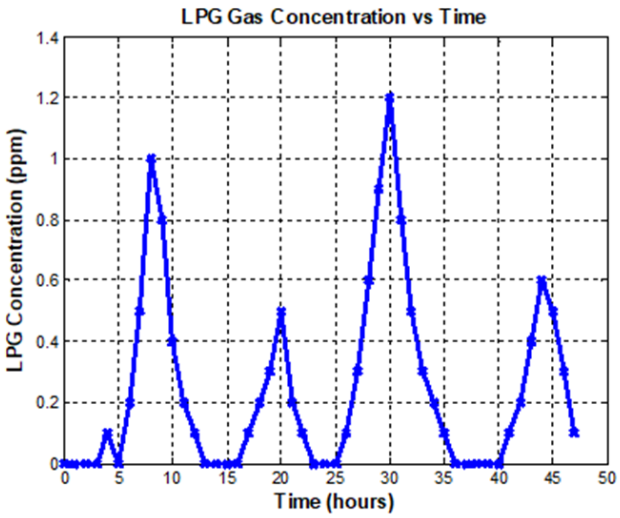

Figure 5: HC-12 Telemetry: Packet Delivery Rate vs Distance for LPG Data Transmission

As illustrated, the HC-12 telemetry data were acquired over a 48-hour period. The data in Figure 2 reveal a smooth two-day temperature profile, characterized by daytime peaks of approximately 30 °C and nighttime minima of 21–22 °C. Figure 3 shows the dataset, which exhibits daily fluctuations characteristic of ambient methane gas concentrations, with daytime maxima of approximately 2.4–2.5 ppm and nighttime minima of 1.78–1.82 ppm. The dataset presented in Figure 4 shows baseline carbon monoxide (CO) concentrations of approximately 0.7–0.8 ppm, representing ambient levels, with peaks reaching up to ~2.0 ppm for local combustion events. Nighttime concentrations return to baseline values of 0.7–0.8 ppm. The smooth temporal variations make this dataset suitable for edge-AI experiments. Finally, the dataset in Figure 5 exhibits baseline LPG concentrations of approximately 0.0–0.1 ppm, representing ambient air, with occasional spikes up to ~1.2 ppm indicating minor leaks events. Nighttime levels return to baseline values of 0.0–0.1 ppm. These smooth temporal variations observed make the dataset suitable for sensor testing, IoT monitoring, and edge-AI detection simulations.

Power consumption analysis revealed that the Atmega328, ESP32, HC-12 module, and associated peripherals consumed approximately 135–165 mA during active telemetry. With a 3.7 V, 4400 mAh Li-Ion battery, the system achieved an operational runtime of 10–12 hours, demonstrating energy efficiency suitable for extended field experiments.

V. Conclusion

The proposed system successfully demonstrated a wireless telemetry framework for a robotic car prototype. Key contributions in this research include Integration of GPS, Atmega328, ESP32, HC-12, and PHP server for real-time monitoring, high telemetry reliability validated experimentally, and energy-efficient and scalable platform suitable for research and educational purposes.

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