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ESP32-Based Temperature and Humidity Monitoring System with Data Logging Capabilities

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Abstract

This paper outlines the development and implementation of a cost-effective, real-time temperature and humidity monitoring system using the ESP32 microcontroller integrated with the DHT22 sensor. The system is designed to collect environmental data and transmit it over a Wi-Fi network to a web-based interface hosted directly on the ESP32. Users can monitor current temperature and humidity levels remotely via any device connected to the same network. The platform is lightweight, scalable, and particularly suitable for applications in agriculture, smart homes, greenhouses, laboratories, and industrial environments where maintaining precise climate conditions is essential. The system also supports customization for data logging and alert triggering, enabling future enhancements like cloud integration and mobile notifications. This project demonstrates how affordable and accessible components can be utilized to build an efficient environmental monitoring solution using IoT principles.

Keywords: RFID Authentication, Multi-Sensor Fusion, IoT Security, Fire Detection, Motion Sensor, ESP32, Smart Home Security.

1. INTRODUCTION

Environmental monitoring plays a crucial role in various domains including agriculture, industrial processes, building management, and scientific research. Temperature and humidity are two fundamental parameters that significantly impact crop growth, product quality, human comfort, and equipment operation[1]. Traditional monitoring solutions often struggle with balancing costs, power efficiency, accuracy, and connectivity options.

The ESP32 microcontroller has emerged as a promising platform for IoT applications due to its dual-core processor, integrated Wi-Fi and Bluetooth capabilities, and rich peripheral set, all while maintaining relatively low power consumption when properly configured[2]. These characteristics make it an ideal candidate for developing versatile environmental monitoring systems that can operate in diverse deployment scenarios.

This paper details the development of a complete temperature and humidity monitoring solution built around the ESP32 platform. The system incorporates precision sensors, implements power-saving strategies, provides multiple data storage options, and supports various communication protocols. We evaluate the system's performance across different metrics including measurement accuracy, power consumption, and reliability

2. RESEARCH OBJECTIVES

The primary objectives of this research include:

- Designing a modular hardware architecture that integrates the ESP32 with high-precision temperature and humidity sensors while optimizing for power efficiency and reliability.
- Implementing firmware that supports configurable sampling rates, local data storage, and multiple communication protocols while minimizing power consumption through effective sleep mode management.
- Evaluating the system's performance in terms of measurement accuracy, power consumption, and reliability under various environmental conditions.
- Demonstrating practical applications of the system in real-world scenarios including agricultural monitoring, industrial process control, and smart home integrations.

3. SYSTEM ARCHITECTURE

The proposed monitoring system follows a modular design approach, separating sensor interfaces, power management, data storage, and communication capabilities. This section details the hardware and software components that comprise the complete solution.

Hardware Design

At the core of the system is the ESP32-WROOM-32 module, which features a dual-core Tensilica Xtensa LX6 microprocessor operating at up to 240MHz, 520KB of SRAM, and 4MB of flash memory[3]. The module integrates Wi-Fi (802.11 b/g/n) and Bluetooth (v4.2 BR/EDR and BLE) connectivity, making it highly versatile for IoT applications.

For environmental sensing, we selected the DHT22/AM2302 sensor for humidity measurements and the DS18B20 for temperature readings. The DHT22 provides relative humidity measurements ranging from 0-100% with an accuracy of ±2%, while the DS18B20 delivers temperature readings with ±0.5°C accuracy from -10°C to +85°C[4]. Both sensors were chosen for their reliability, digital interfaces, and low power requirements.

The power management subsystem incorporates a 3.3V voltage regulator, a battery monitoring circuit, and power gating for peripheral components. This design allows the system to operate from various power sources including a 3.7V LiPo battery, USB power, or solar panels with appropriate charging circuits. Figure 1 shows the complete hardware block diagram.

Data storage is provided through an onboard microSD card slot, allowing for local logging of measurements when network connectivity is unavailable or unreliable. The microSD interface operates over SPI, minimizing the required GPIO pins while maintaining acceptable data transfer rates for the application's needs.

Software Architecture

The firmware follows a layered architecture that separates hardware abstraction, sensor management, data processing, storage management, and communication protocols. Figure 2 illustrates the software component organization.

The base layer implements hardware abstraction, providing uniform interfaces to the various peripherals and managing power states. Above this, the sensor management layer handles initialization, calibration, measurement scheduling, and error detection for the connected sensors.

Data processing components perform filtering, validation, and statistical analysis of the collected measurements. This includes calculating moving averages, detecting outliers, and generating alerts when readings exceed predefined thresholds.

The storage management layer implements a fault-tolerant file system for the microSD card, organizing data in a structured format with timestamps and metadata. It incorporates wear-leveling techniques and transaction safety to protect against data corruption during power failures.

For communication, the system supports multiple protocols:

- HTTP REST API for direct integration with web services and cloud platforms
- MQTT for efficient publish/subscribe messaging with IoT brokers
- BLE for low-power communication with mobile devices
- Serial communication for diagnostic purposes and direct data access

4. POWER MANAGEMENT STRATEGY

To maximize battery life, we implemented a comprehensive power management strategy that includes:

- Configurable deep sleep intervals between measurements, with the ESP32 consuming only approximately 10μA during deep sleep
- Selective powering of sensors only when measurements are needed
- Dynamic CPU frequency scaling based on processing requirements
- Adaptive Wi-Fi power management with connection scheduling
- Optimized data batching to minimize radio transmission events

These strategies collectively enable the system to operate for extended periods on battery power, making it suitable for remote deployment scenarios where frequent battery replacement is impractical.

5. IMPLEMENTATION DETAILS

Hardware Implementation

The prototype was constructed on a custom PCB that integrates all system components in a compact form factor measuring 45mm × 35mm. The PCB design incorporates proper decoupling capacitors, signal integrity considerations, and physical separation between digital and analog sections to minimize noise coupling.

The DHT22 humidity sensor connects to a dedicated GPIO pin using a single-wire digital interface with a 10kΩ pull-up resistor. The DS18B20 temperature sensor operates on the 1-Wire bus protocol, also with an appropriate pull-up resistor. Both sensors are placed away from heat-generating components to ensure accurate environmental readings.

For data storage, the microSD card slot connects to the ESP32 via the HSPI interface, using four GPIO pins for clock, command, and bidirectional data lines. The card operates in SPI mode rather than SDIO to simplify the interface requirements.

The power subsystem includes a BQ24075 battery charging controller that supports input from USB or solar panels, an LTC2941 battery fuel gauge for monitoring charge levels, and an efficient buck converter to provide regulated 3.3V to the system components.

Firmware Implementation

The firmware was developed using the ESP-IDF framework, which provides comprehensive support for the ESP32's features and peripherals. The use of FreeRTOS allows for efficient task scheduling and resource management.

Sensor reading functions were implemented with timeout handling and retry mechanisms to increase reliability. For the DHT22, we employed a bit-banging approach to read the single-wire digital protocol, while the DS18B20 utilized the existing OneWire library adapted for the ESP32 platform.

Data logging follows a structured JSON format that includes timestamps, sensor readings, battery status, and error flags. Each log entry is atomically written to ensure data integrity even during unexpected power failures. The file system implementation uses WL_Flash and FATFS to provide wear leveling and standard file access methods.

The power management functionality leverages the ESP32's deep sleep capabilities, with RTC memory used to maintain state information between sleep cycles. A watchdog timer ensures system recovery in case of software hangs or unexpected behavior.

Network connectivity is implemented with a connection manager that handles Wi-Fi provisioning, reconnection attempts, and fallback modes. The system can operate in station mode for connecting to existing networks or in access point mode for direct connection when infrastructure networks are unavailable.

6. EXPERIMENTAL RESULTS AND EVALUATION

Measurement Accuracy

To evaluate measurement accuracy, we compared the system's readings against a calibrated reference instrument (Fluke 971 Temperature Humidity Meter) across different environmental conditions. Table 1 summarizes the results from tests conducted in various environments.

The mean absolute error for temperature measurements was 0.27°C, with a standard deviation of 0.15°C. For humidity measurements, the mean absolute error was 1.86% with a standard deviation of 0.78%. These results confirm that the system provides acceptable accuracy for most monitoring applications.

Power Consumption

Power consumption was measured under different operating modes:

- Active mode (measuring and transmitting): 120mA average
- Active mode (measuring and storing locally): 68mA average
- Light sleep (CPU paused, peripherals active): 6mA average
- Deep sleep (only RTC and essential circuits active): 10μA average

With a sampling interval of 10 minutes and data transmission once per hour, the system achieved approximately 45 days of operation on a single 3000mAh LiPo battery. This validates the effectiveness of the implemented power management strategies.

System Reliability

Reliability testing involved running the system continuously for 30 days in various environmental conditions. During this period, we tracked the success rate of sensor readings, data storage operations, and wireless transmissions.

Sensor reading reliability was excellent, with 99.7% of attempted measurements completing successfully. Data storage showed 99.9% reliability, with only two failed write operations out of approximately 4,320 attempts. Wireless transmission reliability varied depending on network conditions, ranging from 97.8% in optimal conditions to 85.2% in challenging RF environments.

The recovery mechanisms implemented in the firmware successfully handled all encountered error conditions, with the system automatically returning to normal operation after temporary failures.

7. APPLICATIONS AND CASE STUDIES

Agricultural Monitoring

The system was deployed in a greenhouse environment to monitor conditions for tomato cultivation. Temperature and humidity data collected over a three-week period provided insights into microclimatic variations that correlated with plant growth patterns. The system's wireless capabilities allowed remote monitoring without disturbing the controlled environment, while local data logging ensured no gaps in the dataset despite occasional network connectivity issues.

Industrial Environment Monitoring

In an industrial setting, multiple units were installed to monitor environmental conditions around sensitive manufacturing equipment. The collected data helped identify HVAC system deficiencies that were causing localized temperature variations. The system's alert capabilities notified maintenance personnel when conditions exceeded specified thresholds, enabling proactive interventions before equipment was affected.

Smart Home Integration

For smart home applications, the system was integrated with Home Assistant using the MQTT protocol. This enabled automated control of humidifiers, dehumidifiers, and HVAC systems based on real-time environmental conditions. The BLE interface also allowed direct interaction with smartphones for local monitoring and configuration without requiring internet connectivity.

8. CONCLUSION

This paper presented a comprehensive ESP32-based temperature and humidity monitoring system with data logging capabilities. The implemented solution successfully balances measurement accuracy, power efficiency, connectivity options, and reliability. Experimental results demonstrate that the system achieves precision comparable to more expensive commercial solutions while offering superior flexibility and battery life.

The modular design approach allows for customization to specific application requirements, while the open architecture enables integration with various IoT platforms and services. Power management optimizations make the system suitable for battery-operated deployments in remote locations, addressing a key limitation of many existing solutions.

Future work will focus on extending the sensor array to include additional environmental parameters such as atmospheric pressure, light intensity, and air quality indicators. We also plan to explore mesh networking capabilities to increase coverage area and resilience in challenging deployment scenarios.

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