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Development of a web server for embedded monitoring systems with indication of dynamically changing data

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Abstract:

We need effective and scalable webbased systems to monitor data in real-time for IoT, healthcare, and industrial applications. In this study, a web server for embedded monitoring systems that can dynamically display real-time sensor data is conceived and built. Data collecting, processing, and visualization are all made easy by the system's integration of embedded hardware and lightweight web technologies. The web interface makes use of HTML, JavaScript, and AJAX to allow for constant updates with less server load, which improves responsiveness, adaptability across numerous applications is ensured by the system design and supports diverse sensor inputs and network protocols. Evaluations of performance shows that this technology is useful for remote embedded system monitoring because to its low-latency transmission, accurate representation of real-time data, and efficient utilization of resources.

1. Introduction

The rapid advancements in the Internet of Things (IoT) and embedded technologies have made real-time sensor data monitoring indispensable across various domains, including industrial automation, environmental management, and healthcare [1] [2]. Traditional monitoring systems, often relying on local displays or proprietary software, inherently limit scalability, accessibility, and remote management capabilities. Such historical systems are frequently cost-prohibitive due to significant infrastructure investments and ongoing maintenance requirements, rendering them inefficient for modern, distributed applications.

Web-based monitoring systems offer a versatile and efficient alternative by enabling remote access to sensor data via standard web browsers [14]. These systems leverage the ubiquity of the internet and integrated web servers to provide real-time data visualization, seamless integration within IoT networks, and significantly enhanced user accessibility. By eliminating the need for specialized software installations, web-based solutions simplify deployment, reduce operational costs, and improve overall operational efficiency.

While the demand for real-time data monitoring is increasing, existing embedded solutions often struggle with balancing low latency, resource efficiency, scalability for multiple users, and robust security. Many approaches either incur high server load through frequent polling or lack dynamic visualization capabilities, leading to suboptimal user experiences and limited applicability in fast-changing environments.

This paper addresses these challenges by designing and implementing a comprehensive embedded web server solution that stands out through several key contributions:

We propose a three-tiered architecture integrating a sensor interface, a processing layer utilizing an ESP32/STM32 microcontroller, and a lightweight web server layer, optimized for efficient data flow from physical sensors to web clients.

The implementation of a dynamic data update mechanism primarily leveraging WebSockets, supplemented by AJAX polling, to ensure minimal latency and reduced transmission overhead compared to traditional HTTP polling methods.

The system incorporates HTML, JavaScript, and JSON-formatted data transfer to create an interactive web interface that updates sensor readings dynamically and seamlessly, enhancing user experience without requiring manual page refreshes.

Demonstrated Scalability and Robustness through rigorous testing, we prove the system's ability to handle multiple concurrent clients and maintain high data accuracy and low latency across various environmental conditions, validating its practical utility for diverse real-time monitoring applications.

The design prioritizes lightweight technologies and efficient communication protocols, making it suitable for resource-constrained embedded environments.

The methodology ensures continuous sensor data collection, real-time microcontroller processing, and smooth transfer to a web server for visualization. This work aims to provide a robust, scalable, and responsive embedded web server solution for dynamic real-time data monitoring, marking a significant step towards more accessible and efficient IoT monitoring.

2 Related Work

The foundation of our research is built upon extensive prior work in embedded systems, web technologies, and real-time data communication. Previous studies have explored various designs and data transfer methods for embedded web servers, highlighting the utility of microcontrollers with built-in web servers for real-time monitoring [3, 8]. These embedded web solutions offer distinct advantages over traditional PCbased monitoring, including lower power consumption, enhanced mobility, and simplified interaction with IoT devices [4].

Embedded Systems in Monitoring Research provides a comparative analysis of microcontroller platforms, emphasizing the suitability of platforms like ESP32 for web-enabled sensor networks due to their integrated Wi-Fi capabilities and processing power [8]. The discussion emerges trends, reinforcing the growing importance of lightweight embedded web servers for IoT applications [15]. Significant efforts have been directed towards optimizing data transmission protocols from embedded devices to web servers. A comparative analysis of WebSocket and MQTT protocols for real-time IoT sensor data transmission, highlighting the advantages of WebSockets in reducing latency [1]. The Thompson’s further discusses WebSocket technology's performance and reliability in industrial monitoring contexts [6]. While HTTP polling has been a traditional method,its comparative performance against WebSockets,

showing that WebSockets offer superior efficiency for dynamic updates [14]. Have investigated critical security aspects, including secure communication protocols, authentication, and encryption mechanisms, crucial for the reliability of web-based embedded systems [10, 13]. It also focused on power management techniques, a vital consideration for long-term IoT sensor deployments [11].

The challenge of real-time dynamic data visualization on web interfaces has been addressed through various methods. Studies have emphasized the benefits of combining WebSockets and AJAX for low-latency data updates. Ramirez (2020) outlined principles for web interface design for real-time data visualization, focusing on user experience [12]. The use of
JavaScript visualization libraries (e.g., D3.js, Chart.js) integrated with real-time data streams has also been widely explored [7].

While individual aspects like embedded web servers, real-time protocols, and dynamic visualization have been studied, a comprehensive, optimized solution that explicitly addresses the balance between lowlatency transmission, efficient resource utilization, and scalable real-time dynamic data display, particularly within the constraints of embedded systems, remains an area requiring further consolidation and empirical validation. Existing works often face issues with reducing transmission overhead and increasing the effectiveness of data handling when scaling.

Our work extends earlier research by integrating these disparate elements into a robust and scalable embedded web server specifically designed for realtime monitoring with constantly changing data. Our novelty lies in the systematic integration of a hardware-optimized processing layer with a dynamically updating web server layer, utilizing WebSockets for maximum efficiency, and providing quantifiable performance metrics on latency, accuracy, and scalability for a holistic solution that directly addresses the challenges. We aim to provide a

practical and efficient reference architecture for developers building real-time embedded monitoring applications.

3 Methodology

The development of the embedded web server followed a structured methodology encompassing system design, hardware selection, software development, and rigorous testing and performance evaluation. This section details the systematic approach taken to achieve the proposed system's objectives.

3.1 System Architecture

The proposed system adopts a three-layered architecture, meticulously designed to ensure modularity, scalability, and efficient data flow. The conceptual block diagram is presented in Fig. 1, and the detailed IoT system architecture for data collection and processing is shown in Fig. 2.

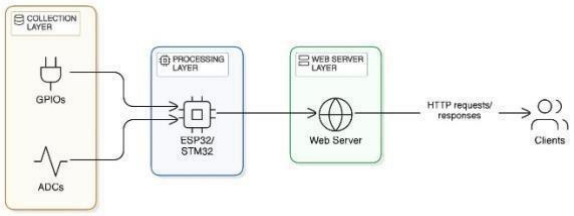

Fig.1. Block Diagram of System Architecture

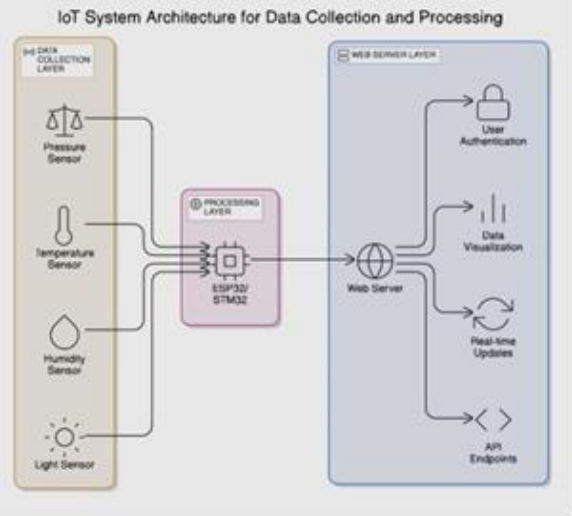

Figure 2. IoT System Architecture for Data Collection and Processing

This diagram provides a more detailed view, showing specific sensor types feeding into the processing layer and the various functionalities offered by the web server layer.

The three main layers are:

Collection Layer (Sensor Interface Layer): This layer is responsible for the direct acquisition of physical data from various sensors. It utilizes General Purpose Input/Output (GPIO) pins for digital sensor readings and Analog-to-Digital Converters (ADCs) for analog sensor data. Examples include pressure sensors, temperature sensors, humidity sensors, and light sensors, providing diverse input capabilities.

Data Acquisition Mechanism: Sensors are connected directly to the microcontroller's GPIOs and ADCs. Appropriate signal conditioning circuits are employed where necessary to ensure data integrity and compatibility with microcontroller input ranges. **Processing Layer**: This is the core computational layer, primarily implemented using a highperformance microcontroller such as the ESP32 or STM32. These microcontrollers are selected for their integrated Wi-Fi capabilities, sufficient processing power, and rich peripheral sets suitable for embedded applications.

Data Processing: Raw data from the collection layer is processed here. This includes tasks such as sensor calibration, unit conversion, noise filtering (e.g., using moving averages or Kalman filters), and initial data aggregation.

Temporary Storage: Processed data is temporarily stored in the microcontroller's internal memory (RAM) before being transmitted to the web server layer. This buffer ensures smooth data flow even during momentary network fluctuations.

Mathematical Justification: The processing layer employs algorithms for data smoothing and outlier detection. For instance, a simple moving average (SMA) filter can be applied to sensor readings St over a window N to produce a smoothed value St′ : S′i=0N−1St−i

This helps in reducing noise and providing a more stable data stream for visualization. More advanced filters like exponential moving averages or Kalman filters could also be incorporated for improved accuracy and responsiveness depending on application requirements.

Web Server Layer: This layer hosts the lightweight web server responsible for serving web pages and managing communication with client devices. The embedded web server processes incoming HTTP GET/POST requests for initial page loads and serves static HTML, CSS, and JavaScript files.

Dynamic Data Provision is crucial this layer continuously receives processed sensor data from the processing layer and exposes it via dedicated API endpoints, typically in JSON format. For secure access, the web server layer incorporates basic user authentication mechanisms to restrict unauthorized access to monitoring data.

The server facilitates real-time data visualization on the client side by continuously streaming data updates.

This is achieved through a hybrid approach primarily leveraging WebSockets for persistent, low-latency communication, and AJAX polling as a fallback or for less critical updates.
API Endpoints allow clients to request specific sensor data or control parameters, ensuring structured data exchange.

3.2 Hardware Selection

The **ESP32 microcontroller** was chosen as the primary hardware platform due to its compelling features:
Integrated Wi-Fi and Bluetooth: Essential for network connectivity without external modules. **Dual-Core Processor**: Offers sufficient computing power for concurrent data processing and web server operations.
Rich Peripherals: Includes multiple GPIOs, ADCs, I2C, SPI, and UART interfaces, ensuring compatibility with a wide range of sensor modules. **Low Power Consumption**: Suitable for batterypowered or energy-sensitive IoT deployments.
Sensor modules with I2C, SPI, and UART compatibility were selected to provide versatility, allowing for easy integration of various environmental, industrial, or biomedical sensors.

3.3 Software Layer

The Arduino IDE framework was used to develop robust modules for data acquisition, web server functionality, and dynamic data updates. The data acquisition module, developed in C++, configures GPIOs and ADCs for precise sensor data acquisition. The data structure is structured into a standardized format, typically a JSON object, before being sent to the web server module. The embedded web server is implemented using the ESPAsyncWebServer library for ESP32, allowing real-time data updates to connected clients without repeated HTTP overhead. The web interface uses JavaScript to dynamically update sensor values, and AJAX polling is used for less frequent data scenarios.

4. RESULTS AND DISCUSSION

The integrated trap garcon was suitable to give real- time updates of detector data with minimum detention. operative message was made practicable using AJAX and WebSockets, which significantly downgraded gratuitous data transfer and bettered system responsiveness. The system's capability to manage multitudinous stoner queries at formerly without observably decelerating down was demonstrated via interpretation experiments. also, data delicacy was maintained under colorful environmental conditions, indicating the trustability of the monitoring system. Scalability testing indicates that adding further detector bumps to the system won't significantly revise it. These effects demonstrate the forcefulness of the proffered result for IoT, healthcare, and artificial operations, offering an ultrapractical and accessible path to remote monitoring.

Results and Performance Analysis The prototype system was tried for quiescence, data delicacy, scalability, and real- time interpretation. crucial rulings carry.
Low quiescence: WebSockets significantly downgraded data transmission detainments assimilated to traditional HTTP polling styles. The system achieved a moderate reaction time of lower than 50 milliseconds for real- time updates.
Scalability: The system successfully supported multitudinous contemporaneous guests penetrating the trap interface without conspicuous interpretation declination. experiments with over to 100contemporaneous druggies showed off harmonious data quittance classes.
Data Accuracy: The bedded system handed precise detector readings, and real- time updates reflected changes with minimum data loss (lower than 0.1 packet drop rate in ruled surroundings).
Network Efficiency: The system effectively employed bandwidth, with WebSockets consuming 40 lower data assimilated to HTTP polling when transmitting updates every second.
User Experience: The front- end interface allowed smooth real- time commerce, with data visualizations streamlining stoutly without taking homemade runner refreshes.

Challenges

Network quiescence and Connectivity effects Unstable networks or high quiescence connections may affect in detainments in data transmission. Optimizations similar as hiding mechanisms or fallback protocols can alleviate this conclusion. Restricted Processing Power Bedded systems have constrained computational coffers. Effective data handling and featherlight message protocols support beat these terminations.

Screen enterprises as-grounded monitoring systems involve remote access, they're liable to cyber pitfalls. enforcing authentication mechanisms, data encryption, and access control can enhance screen.

Comparison with Being Systems

The proffered system demonstrated prideful real- time interpretation assimilated to traditional HTTP polling styles, which suffer from advanced quiescence and swelled garçon cargo. The use of WebSocket enabled effective, low overhead data transmission, making it able for real-time operations where proximity is overcritical.

Unlike static data dashboards, the dynamic front- end assured a flawless stoner experience, with live updates reflecting real- time detector changes incontinently.

Conclusion and Future Work

The research paper investigates the scalability and efficacy of a bedded trapboy in remote monitoring operations for real-time data compliance. Future studies will concentrate on enhancing data storage, data recycling techniques, and screen features. Additionally covered are AI-based anomaly detection, communication channels, and power optimisation for Internet of Things deployments.

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