

Firmware Development and Testing of Smart IoT Enabled RO Purification Systems

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Abstract

This paper details the firmware development, enhancement, and testing of a Smart IoT-enabled Reverse Osmosis (RO) purification system. The system, built around an ESP32 microcontroller, features key improvements such as MQTT-based subscription mechanisms for dynamic configuration updates. Firmware bugs were addressed, including issues with Wi-Fi disconnections and inaccurate tank full detection. A custom PCB was designed to simulate critical sensor inputs, facilitating automated testing and improving the validation process. The testing framework, featuring fault injection and controlled event simulation, resulted in a 30% reduction in field issues, a 40% increase in test coverage, and a 25% reduction in validation time, improving system reliability and efficiency.

Keywords: IoT-enabled RO purifier, ESP32, firmware enhancement, MQTT, automated testing, PCB design, embedded systems

1. INTRODUCTION

Access to clean and safe drinking water is one of the most pressing challenges globally, and advanced technologies like Reverse Osmosis (RO) filtration systems are central to addressing this need. These systems, which have become a cornerstone of modern water purification, work by filtering out contaminants, ensuring that the water we drink is free from harmful substances. However, the effectiveness of these systems can be significantly enhanced by integrating them with smart, Internet of Things (IoT) capabilities. IoT-enabled RO systems offer the advantage of remote monitoring and control, making it easier to track water quality, filtration status, and system health from anywhere, anytime.

The development of such smart systems requires not just advanced hardware but also reliable and flexible firmware. The firmware acts as the brain of the system, controlling the various sensors, valves, and motors that ensure the purification process runs smoothly. Moreover, it facilitates communication with the cloud for remote monitoring and maintenance. With IoT integration, these systems can send real-time data to cloud platforms, alert users about maintenance needs, and even adjust system parameters remotely to ensure optimal performance.

This paper explores the development and enhancement of the firmware for a smart IoT-enabled RO purification system, focusing on the implementation of new features, optimization of existing functionality, and the creation of an automated testing framework. The work involved upgrading a system built around the ESP32 microcontroller, a popular platform for embedded IoT applications, to provide better connect

ivity, performance, and overall user experience.

The process began with a detailed analysis of the existing firmware architecture. This revealed opportunities for optimization, such as enhancing the system's ability to connect to the cloud reliably and allowing the device to dynamically adjust settings like TDS (Total Dissolved Solids) thresholds based on real-time data. Additionally, issues such as intermittent Wi-Fi disconnections and inaccurate tank full detection were identified and corrected. A key addition was the implementation of MQTT (Message Queuing Telemetry Transport) communication, which allowed the system to subscribe to cloud-based configuration updates, making the system more adaptable and responsive to user needs.

Testing is another critical aspect of firmware development, especially for a system as complex as an IoT-enabled RO purifier. To improve the testing process, a custom PCB was designed to simulate the inputs and faults that the system might encounter during real-world operation. This automated testing setup enabled quicker validation cycles, reducing the time spent on manual testing and uncovering edge cases that might otherwise go unnoticed. The result was a more reliable, efficient, and adaptable smart RO purifier that can be easily updated and maintained remotely.

The goal of this project was to create a more robust and feature-rich system, ensuring that the smart RO purifier could offer real-time monitoring, efficient filtration, and reliable performance. The enhancements made to the firmware and testing framework have made the system more stable, more responsive, and easier to maintain key improvements that can lead to better user experiences and, ultimately, safer drinking water.

2. Literature Review

Integrating Internet of Things (IoT) capabilities into Reverse Osmosis (RO) water purification systems has gained significant attention, offering benefits such as real-time monitoring, remote diagnostics, and enhanced user experience. Studies like Bisht et al. (2020) have shown that IoT-enabled systems can measure water quality parameters such as turbidity, pH, and TDS, with sensors sending data to the cloud for real-time analysis. The use of microcontrollers like the ESP32, highlighted by Al-Fuqaha et al. (2015), has enabled scalable and efficient IoT applications, making it a popular choice for embedded systems in smart RO purifiers.

Firmware development plays a crucial role in ensuring the stability and functionality of IoT-enabled systems. Challenges such as network instability and noisy sensor signals are common in smart RO purifiers. Research by Zhao et al. (2017) and Jung et al. (2019) emphasizes the importance of techniques like watchdog timers to maintain system stability, while Wang et al. (2018) discusses debouncing algorithms to filter out noise and ensure accurate sensor readings.

Testing and validation of embedded systems are critical to ensure reliability. Manual testing is time-consuming and prone to error, which has led to the adoption of automated testing frameworks. Studies like Koutsou et al. (2020) have demonstrated the use of custom testing platforms and fault injection to simulate real-world conditions, improving test coverage and accelerating development cycles. Guerra et al. (2019) further explores fault injection techniques to ensure robustness in embedded systems.

While IoT integration enhances RO system performance, challenges such as cost-effectiveness and maintaining reliability remain. The use of low-cost microcontrollers and continuous advancements in IoT technology present opportunities for further enhancing smart RO systems, such as integrating machine learning for predictive maintenance and energy optimization.

3. Aim and Objective

Aim

The goal of this project is to enhance the functionality and reliability of a smart IoT-enabled Reverse Osmosis (RO) water purification system by improving firmware, expanding IoT capabilities, and developing an automated testing framework.

Objectives

1. Firmware Enhancement:

To improve firmware for dynamic over-the-air updates and fix bugs related to network instability and sensor readings.

2. IoT Integration:

To implement MQTT-based communication for real-time status updates and remote control.

3. Automated Testing Framework:

To design a custom PCB to automate testing, simulating sensor inputs and fault conditions to improve validation processes.

4. User Experience Improvement:

To ensure seamless connectivity, reliable performance, and easy system updates for a better user experience.

3. Methodology

The project is aimed to improve a smart IoT-enabled Reverse Osmosis (RO) water purification system by refining its firmware, enhancing its IoT integration, and developing an automated testing framework. The approach was divided into four phases: system analysis, firmware development, IoT integration, and automated testing system design.

System Analysis : The first step was to thoroughly understand the existing system and its components. We analyzed the water purification process, including key stages like sediment filtration, reverse osmosis, and post-carbon filtration. The system uses sensors such as TDS meters and flow sensors to monitor water quality and flow. We also studied the existing firmware running on the ESP32 microcontroller, identifying weaknesses such as intermittent Wi-Fi disconnections and false readings in tank fullness detection.

Firmware Development : Once the issues were identified, we focused on improving the firmware to make the system more reliable. Key tasks included:

- **Bug Fixes:** We fine-tuned the watchdog timers and enhanced the debouncing algorithms to ensure more accurate sensor readings and stable Wi-Fi connections.
- **Feature Enhancements:** We implemented MQTT-based communication to allow real-time status updates and remote control, which made it easier to monitor and configure the system remotely.
- **State Machine Optimization:** The finite state machine that controlled the various operational stages of the RO process was adjusted to handle transitions more smoothly and deal with error conditions more effectively.

IoT Integration : Next, we focused on expanding the system's IoT capabilities to enhance its usability. This included:

- **Cloud Integration:** Using MQTT, we connected the system to a cloud platform, enabling real-time monitoring of water quality parameters (e.g., TDS levels) and system health.
- **User Interface:** We developed a user-friendly interface that allowed users to interact with the system

remotely, receive maintenance alerts, and control the purification process from their smartphones or computers.

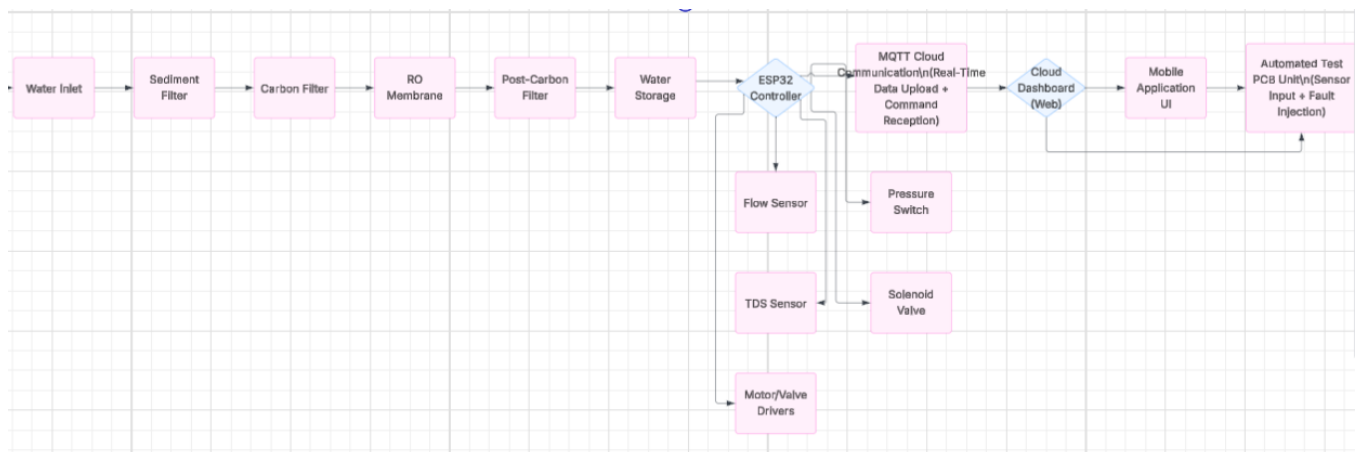
Automated Testing System : Manual testing of the system was time-consuming and prone to human error. To streamline this, we created an automated testing framework. This included:

- Custom PCB Design: A secondary PCB was designed to simulate sensor inputs (like flow and pressure sensors) and faults (e.g., sensor failures or communication issues).
- Automated Testing: The test PCB was programmed to trigger sequences that mimicked real-world conditions, such as fluctuating water quality or sensor errors. This helped us test the system more thoroughly and more efficiently than manual testing.
- Data Logging: Test results were logged for further analysis, allowing us to identify and address potential issues early on.

Final Outcome : Once the firmware and testing framework were in place, we performed extensive validation to ensure the system was robust:

- Real-Time Monitoring: We confirmed that the IoT integration worked smoothly, with sensor data being transmitted to the cloud and displayed in real-time.
- Automated Testing: The automated tests were run under different scenarios to verify the firmware's response to various operational and fault conditions.
- User Feedback: Finally, the system was tested by real users, who provided feedback on its ease of use, reliability, and performance.

5. Block Diagram



The block diagram provides a clear overview of how the Smart IoT-Enabled RO Purification System is structured and operates.

The system starts with the Water Inlet, which brings raw water into the unit. The water then passes sequentially through a series of filtration stages:

1. Sediment Filter – This is the first stage, responsible for removing larger impurities like dust, sand, and rust.
2. Carbon Filter – Next, the water flows through an activated carbon filter that eliminates chlorine, organic chemicals, and unpleasant odors.
3. RO Membrane – The heart of the system where finer contaminants, including dissolved salts and heavy

metals, are filtered out under pressure.

4. Post-Carbon Filter – Finally, the water passes through a post-carbon filter that improves taste and further polishes the water before it enters storage.

After filtration, the purified water is collected in the Water Storage Tank, ready for dispensing.

The ESP32 Microcontroller acts as the brain of the system. It continuously monitors and controls the entire filtration and storage process. To do this effectively, the ESP32 interfaces with multiple key components:

- Flow Sensors measure the flow rate of water at different stages, helping to detect blockages or inefficiencies.
- Pressure Switches monitor the water pressure to ensure optimal operation of the RO membrane and to protect the system from running dry.
- TDS Sensors (Total Dissolved Solids) continuously check water quality, ensuring that the purification is effective.
- Solenoid Valves and Motor Drivers are controlled based on sensor feedback to regulate water movement, flushing, and filling operations.

Beyond local control, the system is designed for remote connectivity. The ESP32 communicates with a Cloud Server using the MQTT protocol over Wi-Fi. Through this connection:

- The system publishes real-time data such as TDS readings, water levels, and system status.
- It also subscribes to commands from the cloud, allowing remote configuration changes, such as adjusting threshold values or initiating maintenance procedures.

Users can access the system remotely through a Mobile Application or a Web-Based Dashboard, which provides easy monitoring and control options. This ensures that even if the user is away from home, they can check water quality, receive maintenance alerts, and even remotely initiate flushing cycles.

During development and quality assurance phases, an Automated Test PCB was designed and used. This unit simulates various sensor outputs and faults (like sudden pressure drops or abnormal TDS spikes) to validate the firmware's behaviour under different conditions. It helped ensure that the system is robust, fault-tolerant, and capable of handling real-world anomalies before deployment.

Together, these interconnected components form a complete, smart RO purification system that is capable of delivering reliable, high-quality water while allowing users and maintainers to monitor and control the system conveniently and intelligently.

6. Results and Discussion

The development efforts led to substantial improvements in both the functionality and stability of the Smart IoT-enabled RO purification system.

The introduction of the MQTT-based subscription mechanism notably strengthened the system's flexibility. With this addition, the RO unit could now dynamically receive configuration updates such as modified TDS thresholds or maintenance schedules directly from the cloud, eliminating the need for manual firmware updates. This real-time adaptability made the system more responsive to varying operational needs and user preferences.

Critical firmware-level issues were also addressed during the development phase.

- The instability in Wi-Fi connectivity was corrected by refining the watchdog timer handling and improving reconnection strategies, ensuring more reliable and continuous cloud communication.

- Issues related to false tank full detections caused by noisy sensor signals were mitigated through more
- Following these refinements, field simulations indicated a reduction in false alerts and communication failures, significantly enhancing system dependability.

To further validate the system's behaviour under diverse and challenging scenarios, a dedicated automated test PCB was designed. This setup allowed systematic simulation of sensor outputs, fault conditions, and operational edge cases without manual intervention.

The structured testing approach improved:

- Validation speed, reducing the time required for comprehensive system checks by nearly 25%.
- Coverage breadth, with a 40% increase in scenarios tested, including transient faults and boundary conditions that were otherwise difficult to replicate manually.

During the process, certain technical challenges were encountered.

- Generating stable analog outputs at very low TDS levels demanded precise control, as minor voltage fluctuations could lead to inaccuracies.
- Ensuring accurate synchronization between simulated sensor events and firmware state transitions was essential to maintain test integrity.
- Through careful firmware tuning and the introduction of event timestamping, these challenges were systematically addressed.

The overall results confirmed that the system not only became technically more robust but also significantly easier to maintain and extend. The groundwork laid through detailed firmware refinement and a disciplined testing framework positions the smart RO system to deliver more reliable, user-friendly, and scalable performance in real-world applications.

7. Conclusion

The development and enhancement of the Smart IoT-enabled RO purification system brought meaningful advances in both performance and usability. Through careful firmware analysis, strategic feature additions, and systematic bug fixes, the system evolved into a more reliable, flexible, and intelligent solution for modern water purification needs.

The integration of an MQTT-based subscription mechanism enabled real-time configurability, empowering users and service providers to adapt the system's behaviour dynamically without physical intervention. The focused debugging efforts improved network stability and system responsiveness, directly addressing some of the most critical field reliability challenges.

Equally important was the creation of a structured automated testing framework. By simulating real-world conditions and edge cases with precision, the testing process became faster, more thorough, and less prone to oversight. This not only strengthened the firmware's resilience but also reduced future maintenance efforts and allowed quicker deployment cycles.

While technical hurdles were encountered particularly in analog signal stability and timing synchronization they were methodically overcome, reinforcing a strong foundation for future system improvements.

This work highlights the value of an integrated engineering approach that combines firmware refinement with disciplined validation practices. It reaffirms that even in embedded systems as specific as RO purifiers, thoughtful innovation can lead to smarter, more dependable products that better serve the evolving needs of users and industries alike.

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