Rural Water Infrastructure Automation System

Abstract

This white paper presents the design, implementation, and field-driven requirements of an automation system developed for decentralized rural water reservoirs.

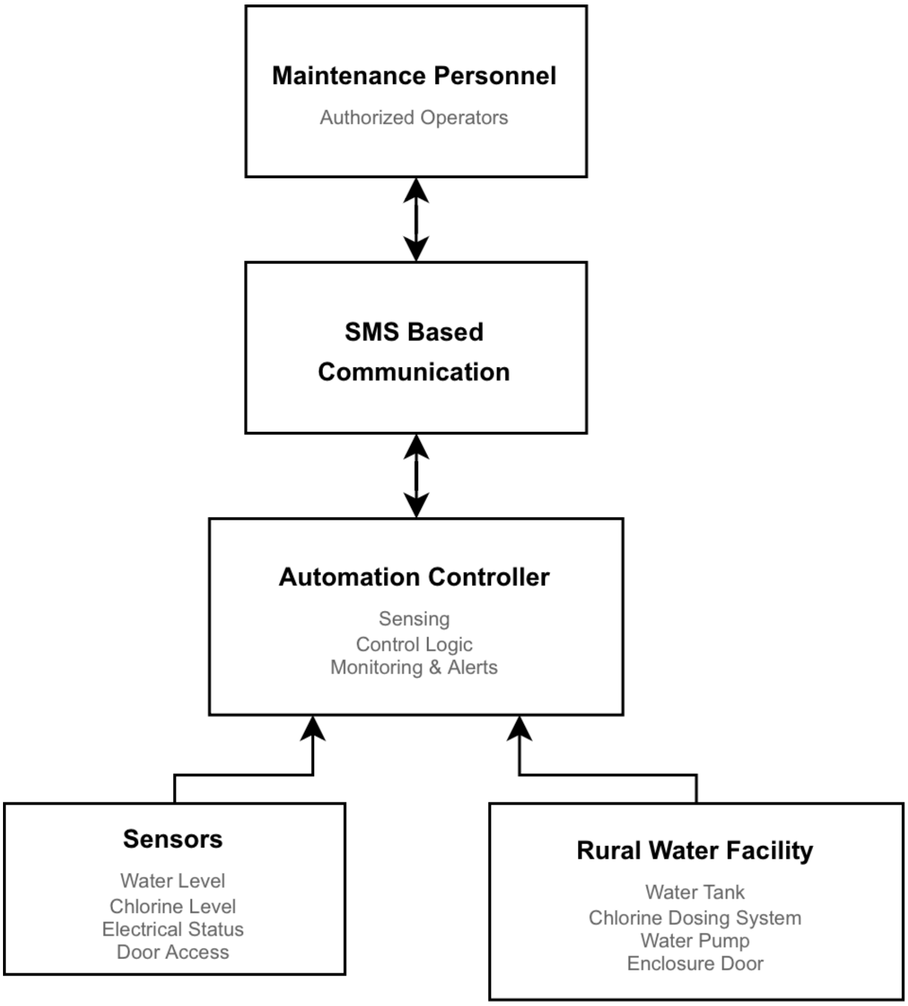

Figure A1 – System overview diagram: functional blocks and field installation context

The system addresses monitoring, control, safety, and operational efficiency problems observed in decentralized village-scale rural water reservoirs. The solution is designed as a low-maintenance, resilient embedded system capable of operating in remote locations with limited connectivity. It enables remote monitoring of water level and chlorine concentration, remote configuration of chlorine dosing schedules, early detection of pump and power failures, and intrusion alerts for physical security. The system was developed as an in-house engineering project in response to real operational needs expressed by regional public maintenance teams, and validated through functional prototype testing and bench-level validation.

1. Introduction

In many rural regions, potable water distribution relies on decentralized water tanks serving individual villages or small settlements. These tanks store water, apply chlorine disinfection, and distribute water to households via electrically driven pumps. Despite their critical role in public health, these systems are often operated manually and monitored only through periodic on-site inspections.

These facilities typically supply potable water to hundreds of households within a village or small rural settlement.

Maintenance teams responsible for these water tanks face several operational challenges:

- Lack of real-time visibility into water and chlorine levels
- Delayed response to equipment failures
- Inefficient manual adjustment of chlorine dosing
- Security risks due to unauthorized physical access

This project was initiated to address these challenges through a practical automation solution tailored to rural conditions.

2. Problem Definition

Figure 2.1 – Typical municipal water reservoir installation in a rural setting

2.1 Operational Visibility Gaps

Maintenance personnel cannot remotely observe water levels or remaining chlorine quantities. As a result, chlorine containers may be depleted without timely intervention, leading to periods of insufficient water disinfection.

2.2 Manual Chlorine Adjustment

Chlorine dosing must be adjusted based on seasonal or temporary changes in water consumption. For example, during holidays with increased water usage, chlorine dosage must be increased. This adjustment traditionally requires personnel to physically visit hundreds of locations.

2.3 Delayed Fault Diagnosis

When water supply interruptions occur, the root cause—pump failure, electrical issue, or thermal protection trip—is unknown until a site visit is completed. This leads to extended downtime due to multiple trips.

2.4 Physical Security Risks

Unauthorized access to water tank enclosures presents a serious public health risk. Any malicious contamination could affect thousands of residents.

2.5 Power Reliability

Electrical outages are common in rural areas. Without monitoring, power failures may go unnoticed until water service is interrupted.

3. System Design Objectives

The system was designed with the following objectives:

- Operate reliably in remote, low-infrastructure environments
- Minimize maintenance complexity
- Provide actionable information rather than raw data
- Enable remote configuration with access control
- Remain functional during power outages long enough to report events

4. Communication Strategy

4.1 Connectivity Constraints

Many water tanks are located in areas with weak or unstable cellular data coverage. Packet-based data communication is unreliable in such environments.

4.2 SMS-Based Communication

Short Message Service (SMS) was selected as the primary communication method due to:

- Higher reliability in low-signal conditions
- Independence from continuous data sessions
- Compatibility with low-power GSM modules

All system interactions—including status reporting, alerts, and configuration—are performed via structured SMS messages.

5. System Architecture

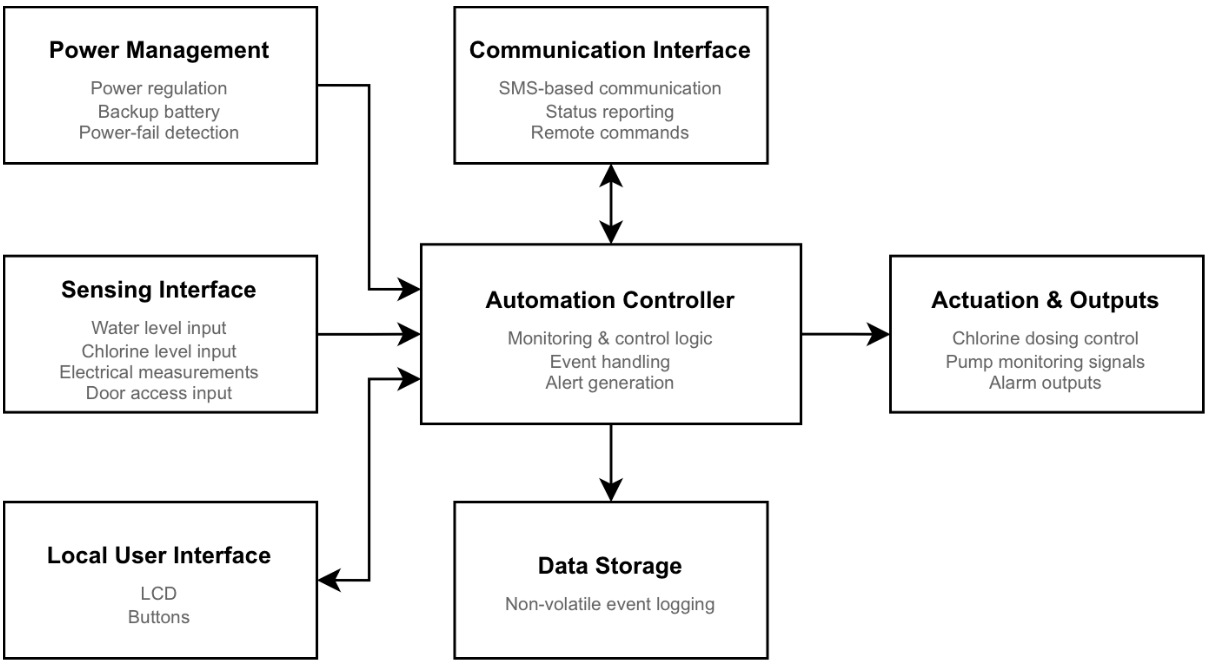

Figure 5.1 – High-level system block diagram illustrating the internal functional architecture of the automation controller and its primary subsystems.

The system is implemented as an embedded controller installed inside the water infrastructure control enclosure.

5.1 Functional Blocks

- Central embedded controller
- GSM communication module
- Sensor interfaces (water level, chlorine level)
- Electrical measurement circuits
- Pump monitoring interfaces
- Backup power subsystem

6. Water Level Monitoring

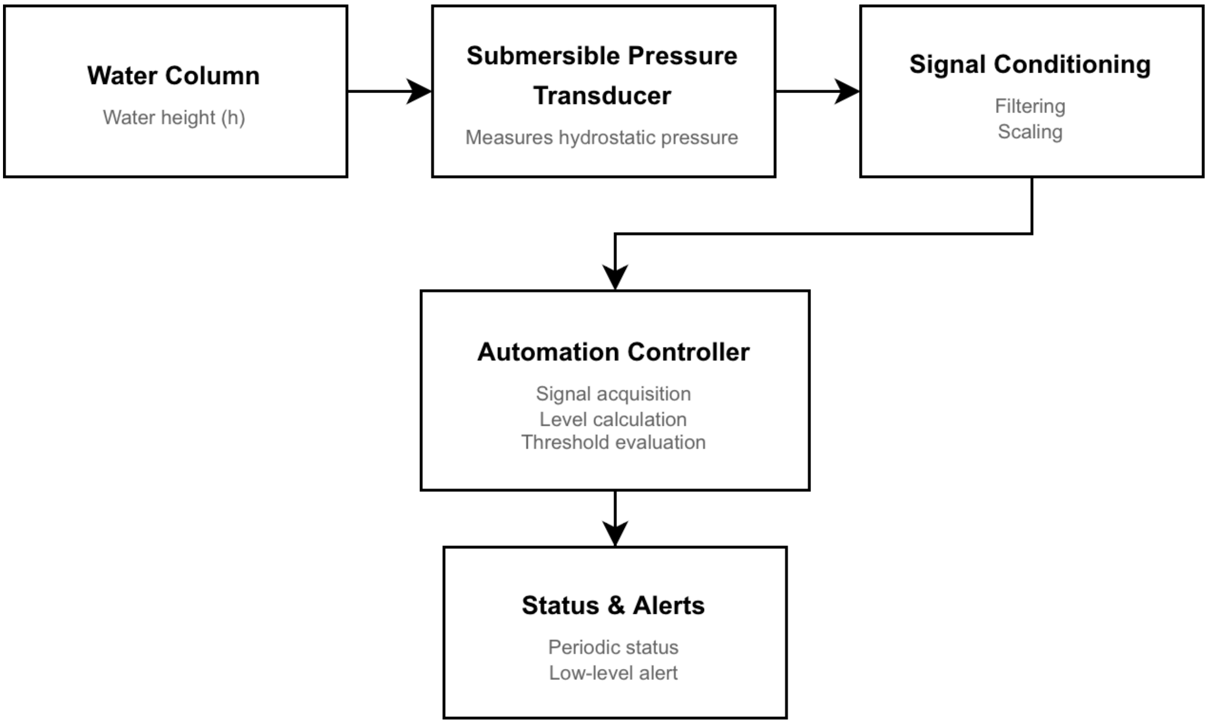

Figure 6.1 – Water level sensing method and signal flow based on hydrostatic pressure measurement and local signal processing.

Water level inside the rural water infrastructure reservoir facility is measured using a submersible pressure transducer. This sensing method was selected due to its suitability for large-volume reservoirs, mechanical simplicity, and minimal exposure to external disturbances.

The transducer provides a pressure-proportional electrical signal corresponding to the water column height. The signal is conditioned and processed locally by the embedded controller, converted into a usable level representation, and included in periodic status messages.

Threshold-based alerts notify personnel when water levels fall below predefined limits.

7. Chlorine Level Monitoring

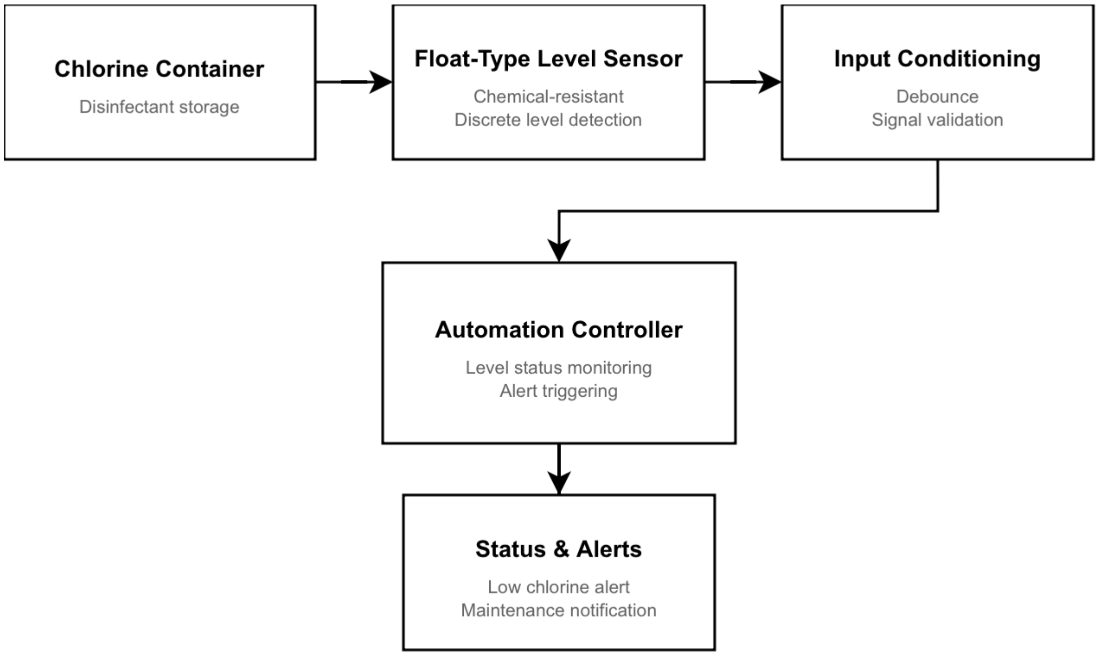

Figure 7.1 – Chlorine container level sensing arrangement using a float-type sensor for low-level detection and alert generation.

The chlorine container level is monitored using a float-type level sensor. This sensing approach was deliberately chosen due to its higher chemical resistance and long-term reliability when exposed to chlorine-based disinfectants.

The sensor provides discrete level information that allows the system to detect low-chlorine conditions reliably. When predefined minimum levels are reached, alert messages are generated to prevent disinfection interruptions and associated public health risks.

8. Remote Configuration via SMS Commands

All configuration changes are performed through structured SMS commands. The command format follows a strict and predictable structure:

(PASSWORD) SET (PARAMETER) (NEW_VALUE)

In this structure:

- PASSWORD authenticates the sender
- PARAMETER specifies the setting to be modified (e.g., OPERATION, IDLE, TIMING, CONTACT, PASSWORD)
- NEW_VALUE defines the updated value for the selected parameter

System status information is requested using the following format:

(PASSWORD) STATUS

Upon receiving this command, the system responds with a consolidated status message containing all relevant operational information.

Critical alerts, such as intrusion events, power failures, or pump faults, are automatically sent to preconfigured phone numbers without requiring any user request.

9. Pump Monitoring and Fault Diagnosis

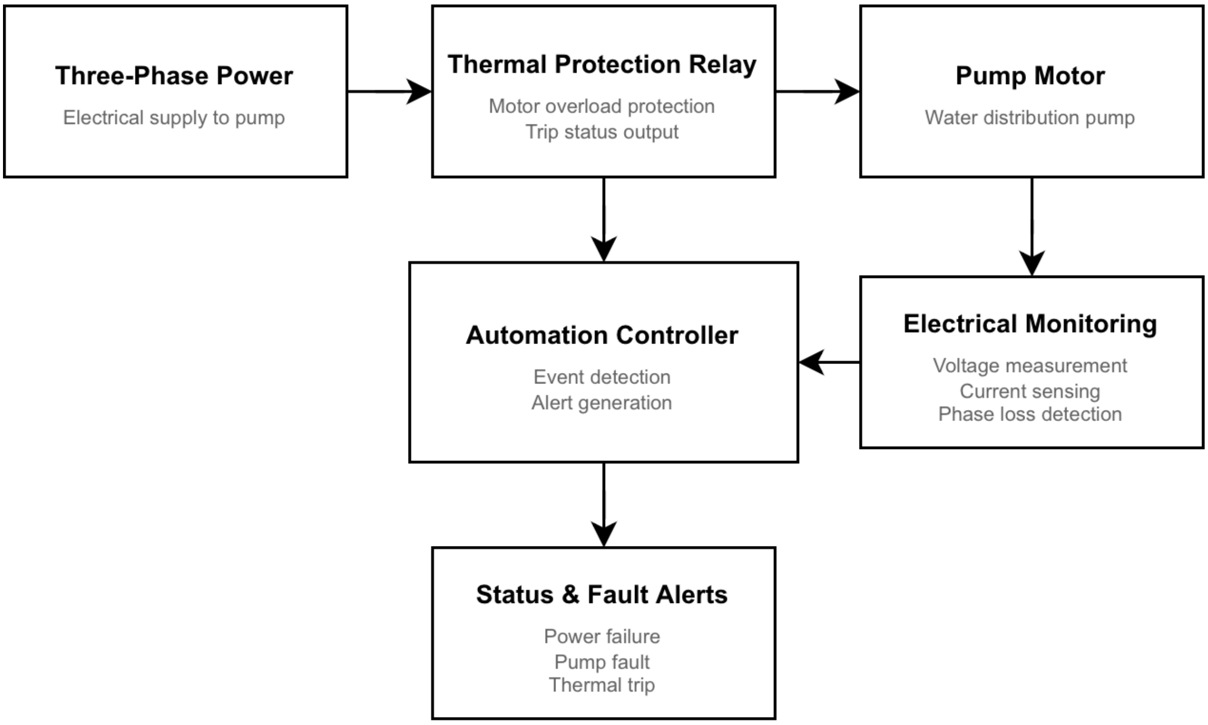

Figure 9.1 – High-level schematic illustrating pump electrical monitoring through voltage, current, and thermal relay status for fault diagnosis.

9.1 Electrical Measurement

Each phase of the pump supply is monitored for:

- Voltage presence
- Current draw

This allows detection of:

- Phase loss
- Motor overload
- Electrical supply failure

9.2 Thermal Protection Monitoring

The system monitors the state of the thermal relay protecting the pump motor. Trip events are reported immediately.

9.3 Diagnostic Value

By combining voltage, current, and thermal data, maintenance teams can infer probable fault causes before visiting the site.

10. Physical Security Monitoring

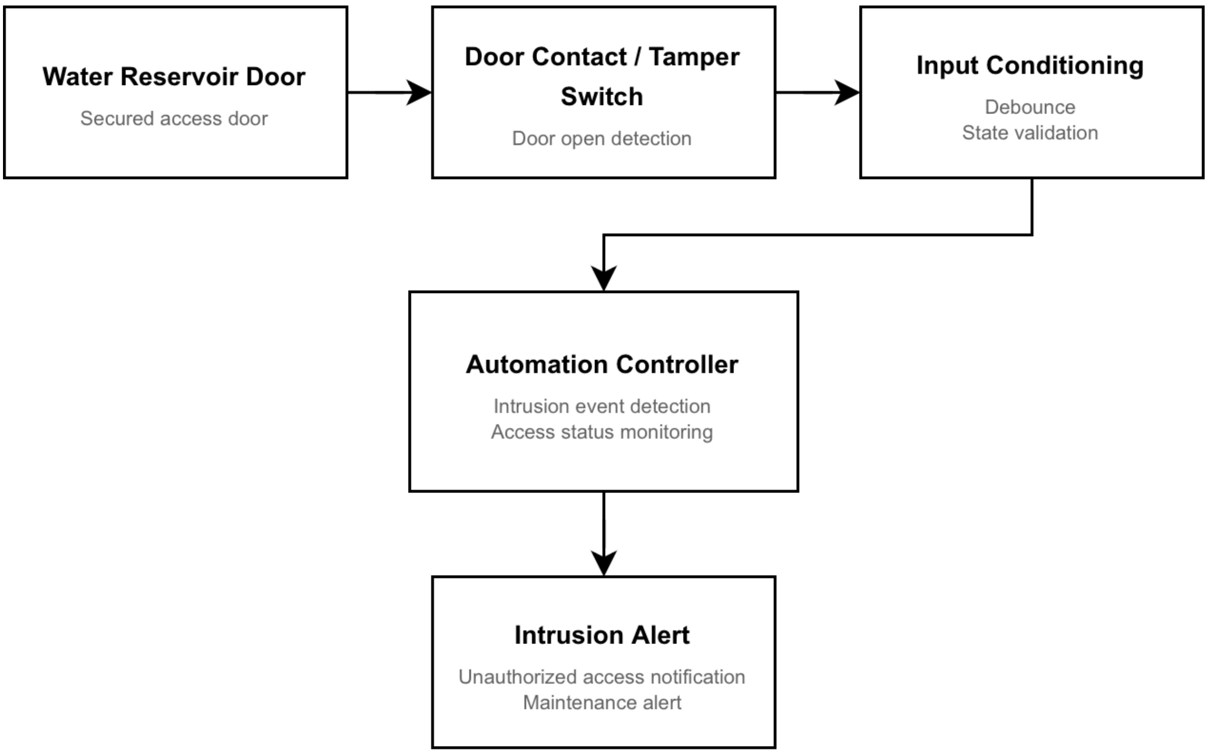

Figure 10.1 – Door intrusion detection mechanism for monitoring unauthorized access.

Door access to the water tank enclosure is monitored using a tamper detection mechanism. Unauthorized opening triggers immediate SMS alerts.

This feature addresses intentional or accidental contamination risks.

11. Power Failure Detection and Backup Operation

11.1 Backup Power Design

A dedicated battery allows the system to:

- Detect loss of mains power
- Send a power failure notification
- Shut down gracefully to preserve energy

11.2 Power Restoration Reporting

When mains power is restored, the system sends a corresponding notification.

12. Security and Access Control

12.1 Authentication

All remote commands require a valid password embedded in the SMS command format.

12.2 Authorization

Only pre-registered phone numbers are allowed to issue configuration commands.

12.3 Fail-Safe Behavior

Incorrect command formats or authentication failures result in no system state change.

13. Embedded Software Architecture

The firmware was developed as a deterministic, event-driven system running on an STM32F1 series microcontroller. Task scheduling, inter-task communication, and timing-critical operations are handled by the RTOS to improve system determinism, event prioritization and maintainability. A Quectel M95 GSM module is used for SMS-based communication.

These components were selected based on their availability, maturity, and proven reliability in embedded and industrial applications.

Key software characteristics include:

- Clear separation of sensing, communication, and control logic
- Watchdog-based fault recovery
- Robust parsing and validation of SMS commands

The software prioritizes reliability and predictability over complexity.

14. Hardware Design

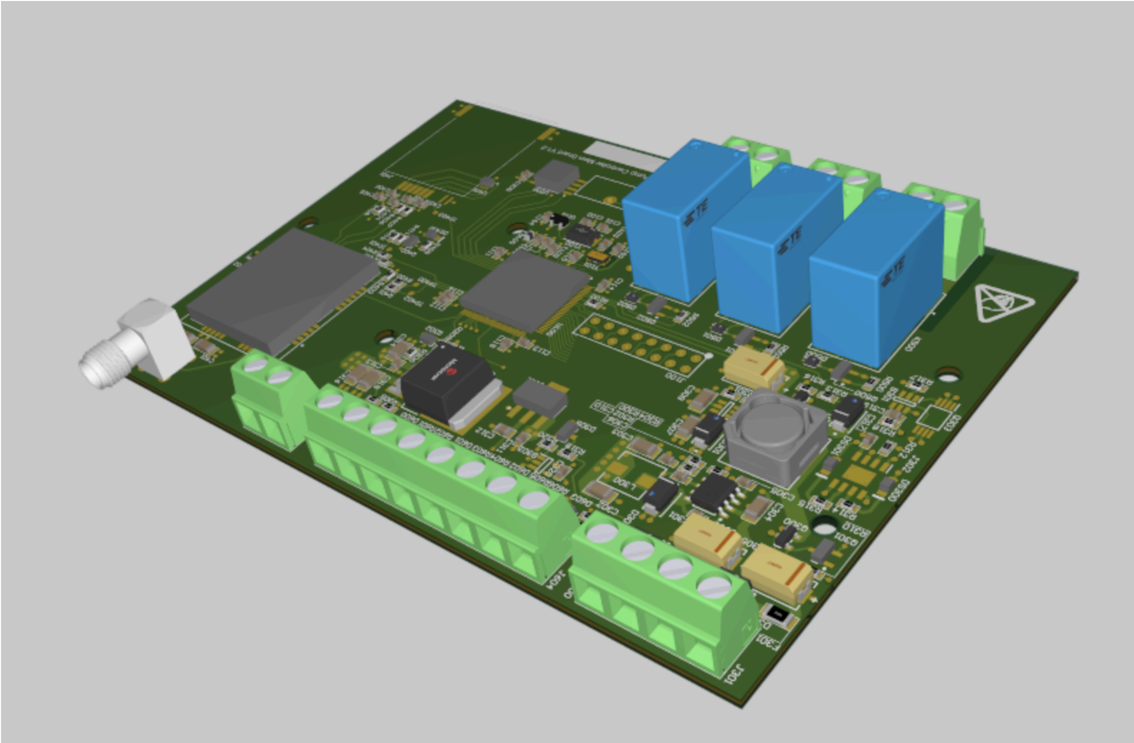

Figure 14.1 – Isometric view of the main control PCB integrating sensing, communication, power management, and control subsystems.

14.1 Hardware Design Considerations

The hardware architecture was developed with a focus on long-term unattended operation in rural water infrastructure environments. Design decisions were guided by practical field constraints, including electrical instability, limited on-site maintenance access, and the need for predictable system behavior.

Key considerations include:

- Robust power architecture supporting both mains-powered and battery-backed operation
- Electrical domain separation between sensing, control, communication, and high-power actuation paths
- Protection strategies against voltage transients, electromagnetic interference, and inductive load switching effects
- Connectorized and modular interfaces to simplify field replacement and maintenance procedures

These considerations aim to improve system reliability, serviceability, and fault tolerance without increasing architectural complexity.

14.2 Mainboard Functional Overview

The main control board integrates all core system functions required for autonomous operation of rural water infrastructure facilities. The following subsystems are implemented on the mainboard:

1. Microcontroller unit (MCU) executing control logic and system coordination
2. Power supply circuits providing regulated rails for all subsystems
3. Li-ion battery and charging circuits enabling backup operation during power outages
4. GSM communication module with SIM card interface for SMS-based connectivity
5. Interface connectors for the LCD and button board used for local interaction
6. Relay circuits controlling chlorine dosing pumps
7. Electrical measurement circuits for monitoring voltage and current of the main water pump
8. Sensor interface circuits for water level and chlorine level sensing
9. Door intrusion sensor input and conditioning circuits
10. On-board non-volatile flash memory for persistent firmware logging and event recording

14.3 PCB Design

The PCB layout was developed to support reliable operation in electrically noisy and maintenance-constrained rural infrastructure environments. Layout decisions were driven by signal integrity, safety, and long-term service considerations rather than density optimization.

Key layout and implementation aspects include:

- Clear separation of low-level analog sensing circuits, digital control logic, and high-power switching paths to reduce noise coupling
- Isolation of pump actuation and relay-driven loads from sensitive measurement and communication circuits
- Routing strategies that minimize ground loops and reduce susceptibility to conducted and radiated interference
- Component placement and connector orientation selected to simplify inspection, replacement, and troubleshooting during field maintenance

15. Deployment and Validation

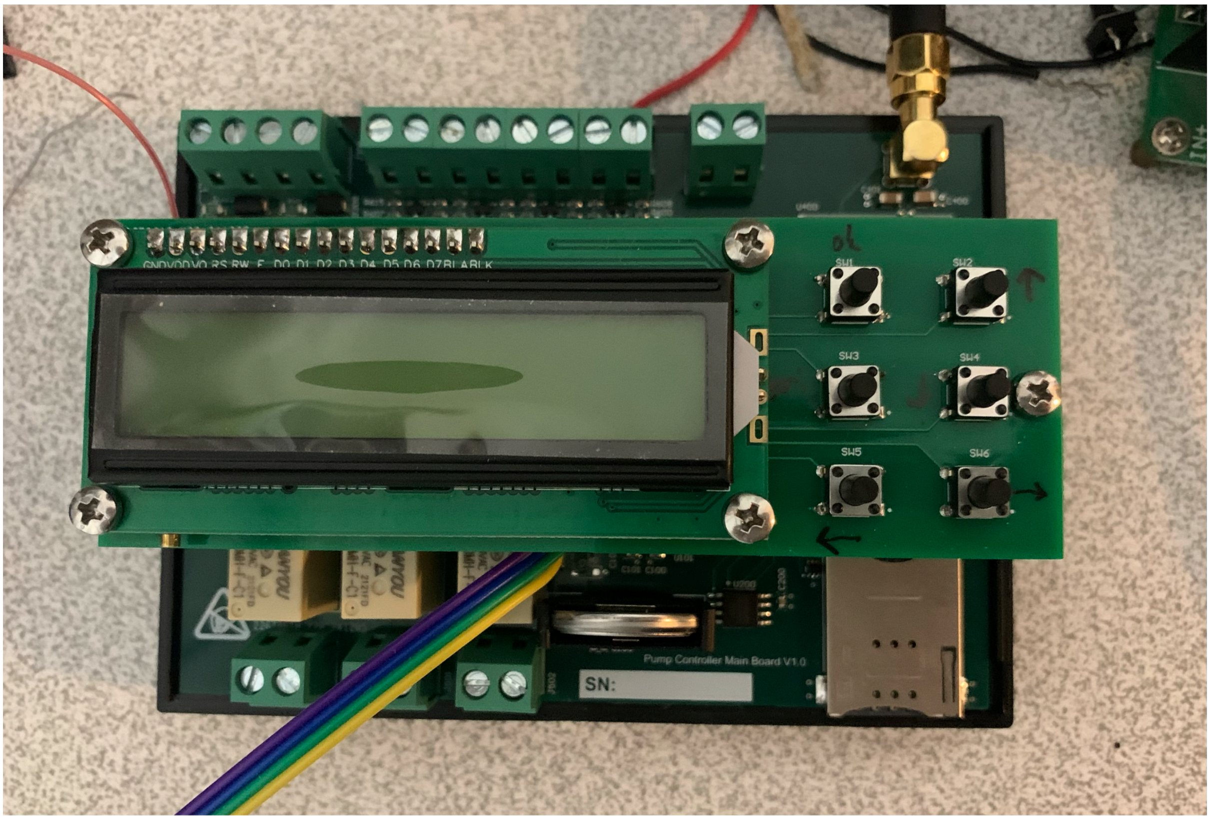

Figure 15.1 – Prototype system used for bench-level functional validation

At the time of writing, the system remains at the prototype validation stage. A functional prototype was built to validate system architecture, hardware design, and firmware behavior in a controlled development environment. The system architecture and design decisions were shaped to support scalable deployment across multiple rural water facilities without requiring significant modification.

Validation activities focused on:

- Verification of SMS communication logic and command handling
- Functional testing of sensing, monitoring, and alert mechanisms
- Review of maintainability and usability for rural water infrastructure maintenance workflows

The system has not yet undergone long-term field deployment. Preparations are underway for installation in a rural water infrastructure reservoir facility for real-world operational testing.

16. Impact and Benefits

The system delivers measurable operational improvements:

- Reduced response time to failures
- Improved public health protection
- Lower operational costs
- Increased system transparency

Systems of this type reduce dependence on manual field inspections and help ensure consistent water disinfection practices in underserved rural communities, contributing to public health resilience.

17. Limitations and Future Work

Potential future enhancements include:

- Integration with centralized dashboards
- Encrypted messaging
- Predictive maintenance analytics

These features were intentionally excluded from the initial design to preserve simplicity and reliability.

18. Conclusion

This project demonstrates that carefully engineered embedded systems can significantly improve rural water infrastructure without requiring complex or expensive technologies. By focusing on real operational constraints and prioritizing reliability, the system provides a practical model for scalable rural water automation.

Appendix A – Author Contributions and Disclosure

The author contributed to the technical development of the system, including system architecture definition, hardware design, embedded firmware development, system integration, and validation activities, within the scope of an engineering organization.

This document is intended to provide a high-level technical overview of the system design rationale and operational concepts. It does not disclose proprietary schematics, source code, or confidential implementation details.

The focus of this document is technical documentation rather than commercialization or policy considerations.