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Design and Implementation of a Low-Power, Real-Time, Water-Quality Monitoring System for Fish Transport

Master Thesis

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Abstract

Live fish transport poses significant challenges for aquaculture, particularly in maintaining optimal water quality during transit. This thesis presents the design and implementation of a lightweight, low-power, real-time monitoring system for use in mobile fish transport tanks. The system continuously measures critical parameters: dissolved oxygen, temperature, and turbidity which are key indicators of fish health and stress.

The hardware integrates commercial optical and nephelometric sensors with a Nordic nRF52832 Bluetooth Low Energy (BLE) microcontroller. Sensor data is transmitted wirelessly via a browser-based Web Bluetooth interface and displayed locally on an LCD. Visual and audible alerts are triggered when parameters exceed safe thresholds.

A UART multiplexer enables interfacing both RS-232 and RS-485 sensors through a shared UART port, reducing hardware complexity. Although full dual-sensor integration was limited by the oxygen sensor's automatic mode, the architecture supports polling-based operation and was validated with each sensor independently. Powered by a 2800 mAh Li-ion battery, the system achieved a runtime of approximately 6 days.

Controlled testing using simulated contamination (milk and carbonated water) confirmed system responsiveness and reliability. The results demonstrate a scalable and low-maintenance solution for enhancing fish welfare during transport, with potential applications across aquaculture and environmental monitoring.

Preface

This thesis was submitted as part of the Master's degree in Electronics Engineering at the University of Bologna and was conducted during the Erasmus+ Exchange Program at the Norwegian University of Science and Technology (NTNU), during the spring semester of 2025, under the course TK4550 Engineering Cybernetics Specialization Project.

The project was carried out in collaboration with the Department of Engineering Cybernetics at NTNU and was supervised by Prof. Jo Arve Alfredsen. The goal of this thesis was to design and implement a real-time, low-power water quality monitoring system for live fish transport applications. The topic brought together embedded systems design, environmental sensing, wireless communication, and system-level integration offering a highly practical and multidisciplinary engineering challenge.

I would like to express my sincere gratitude to my supervisor, Prof. Jo Arve Alfredsen, for his continuous support, insightful feedback, and guidance throughout this project.

I am also thankful to Mr. Anders Rønning Petersen, who supported the hardware development. His help with soldering, electronics components, and valuable advice are greatly appreciated.

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Chapter 1

Introduction

Ensuring the health and welfare of fish during transport is a critical aspect of sustainable aquaculture and fisheries management. In Norway, fish hatcheries play an essential role in supporting the conservation of wild salmon and sea trout populations. Transport of broodstock and juvenile fish between rivers and hatcheries is a key operational activity, yet it is often performed using basic setups such as car trailers equipped with water tanks lacking water recirculation and advanced monitoring systems as shown in Figure 1.0.1. Without effective real-time monitoring, fish are exposed to rapidly changing and potentially harmful water quality conditions during transport, increasing stress and mortality risks.

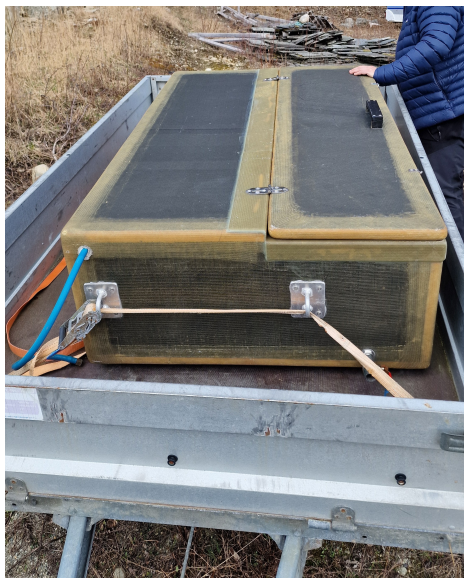


Figure 1.0.1: Typical mobile fish transport tank used in field conditions.

Among the most influential parameters affecting fish welfare during transport are dissolved oxygen (DO), oxygen saturation %, water temperature, and turbidity. Fluctuations in these parameters can compromise fish health, particularly in confined, non-recirculating transport tanks where metabolic activity and waste accumulation can quickly alter water conditions. Manual oxygenation is typically used, but without continuous feedback on actual water quality, operators must rely on estimation and experience. This lack of awareness presents a significant limitation for ensuring safe and optimal transport conditions.

1.1 Objective

The goal of this project is to develop a lightweight, low-power, embedded monitoring and alert system for fish transport tanks. The system is designed to provide operators with real-time, wireless access to key water quality parameters and immediate visual and audible alerts when thresholds are exceeded. The primary objectives of this thesis are to:

- Design and implement a battery-powered, real-time water-quality monitoring platform focused on dissolved oxygen, Temperature and turbidity measurements.
- Develop embedded firmware and a user interface (SPI-driven LCD and Web Bluetooth WebUI) for live data display and remote threshold configuration.
- Validate system performance through controlled trials in model media and demonstrate field readiness for fish transport applications.

1.2 Outline

This report is organized as follows:

1. **Background & Related Work** (Chapter 2) reviews sensing principles for dissolved oxygen and turbidity, and surveys existing portable monitoring systems.
2. **System Design** (Chapter 3) details the hardware architecture, power management, sensor interfaces, and user-interface components.
3. **Software Implementation** (Chapter 4) describes the embedded firmware and Web application development.

4. **Testing Methods** (Chapter 5) presents test mechanisms for controlled trials.
5. **Results & Discussion** (Chapter 6) presents results and discussion on milk and carbonated drink experiments, including power consumption of the system.
6. **Conclusion & Future Work** (Chapter 7) highlights key findings and proposes enhancements for broader aquaculture deployment.
7. **Appendices** (Chapter 8) includes raw data tables, and code repository link.
8. **Bibliography** lists all cited literature and technical documents.

Chapter 2

Background and Literature Survey

This chapter provides the technical and application context for our work by first surveying existing portable water-quality monitoring platforms, then reviewing the core sensing principles for dissolved oxygen and turbidity. Finally, we present the fish specific water-quality criteria that should be achieved to make sure fishes are in good health.

2.1 Existing Portable Monitoring Platforms & Limitations

A wide range of commercial and academic systems have been developed for field-deployable water-quality monitoring. Commercial multi-parameter platforms such as the YSI EXO Buoy [1] and Ellenex IIoT sensor nodes [2] integrate dissolved-oxygen, turbidity, pH, and conductivity probes in rugged enclosures with cellular or LoRaWAN connectivity and cloud dashboards. While they offer high accuracy and unattended operation, these solutions typically consume several hundred milliwatts continuously, rely on proprietary firmware, and incur recurring data-plan costs.

Modular “plug-and-play” offerings like Libelium’s Smart Water Sensor line [3] demonstrate flexible probe mounting and Docker-based server backends. However, they remain relatively bulky, require external gateways, and often lack onboard displays for immediate feedback.

Academic prototypes have explored ultra-low-power microcontroller platforms with wireless sensor networks [4] or ZigBee streaming [5]. These designs typically target a single parameter (e.g., pH, temperature, or turbidity) or, if multi-parameter, require multiple serial ports or I²C buses beyond what low-cost development kits provide. Few integrate both dissolved-oxygen and

turbidity sensing in one enclosure, and combine an onboard LCD for local alarms with a Web-Bluetooth interface for real-time remote monitoring while maintaining an average power draw below 100 mW suitable for multi-day fish-transport missions.

These gaps, high power consumption, parameter-limited sensing, dependence on external gateways or apps, and lack of dual local or remote UI directly motivate the present work: a battery-powered, multiplexed dissolved oxygen + turbidity monitor with both onboard display and browser-based BLE connectivity, optimized for the requirements of live-fish transport.

2.2 Dissolved Oxygen Sensing Techniques

Dissolved oxygen (DO) is a key indicator of water quality, directly affecting aquatic metabolism, biogeochemical cycles, and fish health. Two principal sensing paradigms dominate commercial and research instruments:

- **Electrochemical (Clark-type) sensors:** These probes consist of a gas-permeable membrane covering a cathode and anode immersed in an electrolyte. Oxygen diffuses through the membrane and is reduced at the cathode, producing a current proportional to the partial pressure of dissolved O_2 . Clark sensors offer fast response times but require regular calibration, stirring to avoid boundary-layer effects, and maintenance to replace fouled membranes.
- **Optical optodes:** Optical DO sensors use luminescent dyes that dim or fade when exposed to oxygen. Measurement of the fluorescence lifetime (or intensity ratio) provides a direct, non-consumptive readout of O_2 concentration. Optical methods typically consume less power, eliminate the need for stirring, and maintain stable calibration over extended deployments [6].

2.3 Turbidity Measurement Principles

Turbidity indicates the cloudiness of water caused by suspended particles, and is typically expressed in Nephelometric Turbidity Units (NTU). Two common optical methods are used:

- **Nephelometry (90° side-scatter):** A collimated light source illuminates the sample while a detector positioned at 90° measures the intensity of scattered light. This geometry maximizes sensitivity at low

turbidity levels and is standardized by ISO 7027-1 and EPA Method 180.1 [7].

- **Turbidimetry (forward-scatter/attenuation):** A detector aligned with the light source measures the reduction in transmitted light intensity. This simpler arrangement operates at lower voltages with analog outputs but generally provides lower sensitivity compared to nephelometry.

2.4 Water Quality Criteria

Fish transport places strict demands on water quality to minimize physiological stress and mortality. Our system measures four key parameters: dissolved oxygen concentration (μM) which is the absolute amount of oxygen dissolved, oxygen saturation (%) which is how that concentration compares to the maximum that water can hold under the current temperature and pressure. Temperature ($^{\circ}\text{C}$) and turbidity (NTU) are also measured which is water clarity and system should trigger alarms when values approach critical thresholds. The recommended ranges for juveniles and broodstock are summarized in Table 2.4.1.

Table 2.4.1: Recommended Water-Quality Ranges for Live-Fish Transport

Parameter	Unit	Juveniles (Ideal)	Broodstock (Ideal)
Dissolved O ₂	μM (mg/L)	250–375 (8–12)	220–310 (7–10)
O ₂ Saturation	%	85–100	90–100
Temperature	$^{\circ}\text{C}$	10–14	6–12
Turbidity	NTU	< 10	< 8

These all are very critical parameters for fish health during transport, lower levels of the dissolved oxygen affects growth and reproductive success of the fishes [8], optimum temperature is essential for fish metabolism and overall health whereas high turbidity values can cause gill irritation [9] and reduced oxygen uptake [10]. So if ideal ranges mentioned above are not available, fish begin to experience stress; we configure our device to alarm when parameters cross the following limits:

- **Dissolved O₂:** alarm if < 156 μM (5 mg/L)
- **O₂ Saturation:** alarm if < 85 %

- **Temperature:** alarm if $> 16\text{ }^{\circ}\text{C}$
- **Turbidity:** alarm if $> 12\text{ NTU}$

Dissolved oxygen is usually measured in two units, mg/L and μM . We need to multiply our reading in mg/L by 31.25 to get μM , as the molecular weight of O_2 is 32 g/mol.

- **mg/L** is “milligrams of O_2 per liter of water.”
- **μM** is “micromoles of O_2 per liter.”

These criteria are drawn from aquaculture transport studies and industry guidelines. By presenting both the ideal and alarm setpoints, our system can be tuned for different life stages and transport durations, ensuring fish welfare throughout the journey.

Chapter 3

System Design

The system is designed to provide a lightweight, low-power embedded solution for real-time monitoring of key water quality parameters: dissolved oxygen (DO), temperature, and turbidity, during the transport of live fish in mobile water tanks. The system must operate reliably under the constraints of small-scale transport setups, where limited space, power availability, and environmental variability present significant challenges. It must further offer an intuitive and accessible user interface to enable operators to maintain optimal transport conditions in real time. Key design requirements identified during the project include:

- Continuous monitoring of DO, temperature, and turbidity.
- Real-time visual and audible alerts when parameters exceed safe thresholds.
- Wireless access through a mobile-friendly interface without requiring installation of dedicated apps and public internet.
- Low power consumption to support battery operation during extended transport.
- Scalability and modularity to support future enhancements, such as automated control of DO levels.

An overview of the system architecture is shown in Figure 3.0.1. The system integrates commercial sensors with a Bluetooth Low Energy (BLE)-enabled microcontroller, supported by a modular power management subsystem. Sensor data are processed and transmitted to the user interface over BLE, enabling visualization and interaction via a Web Bluetooth application.

Additionally, the system includes local displays and audible/visual alerts to ensure that critical information is available even without an active wireless connection.

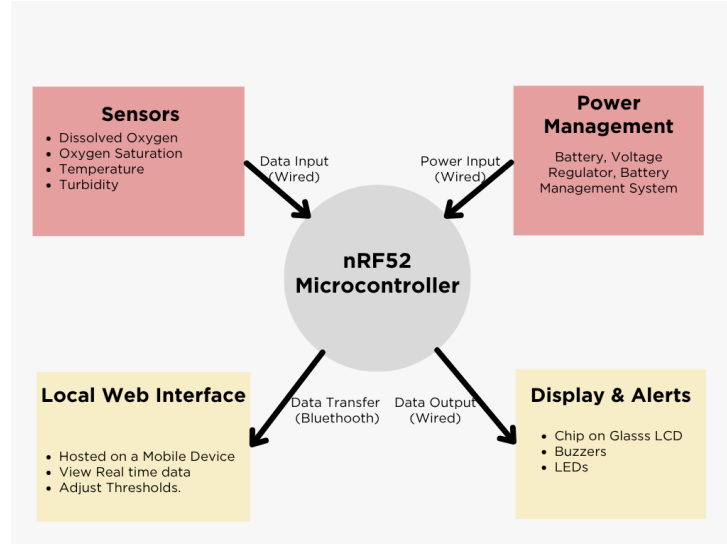


Figure 3.0.1: Top-level System.

The following subsections describe the key components of the system in more detail.

3.1 List of Components

All of the Hardware components used in our system are mentioned below:

1. **Aqua Optode 4531D:** Oxygen and Temperature sensor.
2. **RS-ZD-N01 Renkeer RS485:** Turbidity sensor.
3. **Nordic nRF52 DK:** Microcontroller based on nRF52832 SoC.
4. **Soldered 333014 IC:** Li-ion charger with protection.
5. **PTM2-3-S12-S IC:** 3.3 to 12 V DC/DC Converter.
6. **LTC3531-3.3:** 3.3 Buck-Boost DC/DC Converter.
7. **ICL3232 IC:** RS232 to UART Converter.
8. **MAX3485 IC:** RS485 to UART Converter.

9. **74HC4052 IC:** Dual 4-channel Multiplexer.
10. **AI-1231-TWT-4 Buzzer:** 5V Audio Buzzer.
11. **NHD-C12864LZ LCD:** Chip on Glass LCD Module.
12. **2N7000 IC:** N Channel Mosfet.
13. **18650 Cell:** 2800 mAh Li-ion Cell.
14. **Capacitors, Inductors & Resistors**

3.2 Microcontroller Unit

The microcontroller unit (MCU) forms the central hub of the system, coordinating sensor data acquisition, processing, wireless communication, and alert triggering. Given the need for long-duration operation on battery power in a mobile environment, the MCU must combine ultra-low power performance with robust support for Bluetooth Low Energy (BLE) communication and flexible sensor interfacing.

After evaluating multiple platforms, including ESP32, STM32WB55, and TI CC2640R2F, the Nordic nRF52 DK, based on the nRF52832 SoC, was selected. The nRF52832 offers an optimal combination of low power operation, BLE 5.0 capabilities, sufficient processing resources, and versatile peripheral support (UART, I2C, SPI), making it well-suited to this application [11]. Comparative study performed between multiple controllers are mentioned in Figure 3.2.1.

In the system architecture, the nRF52 acquires data through 74HC4052 Multiplexer from the oxygen sensor via an RS232-to-UART interface, and from the turbidity sensor via an RS485-to-UART interface. This data is processed locally and transmitted wirelessly over BLE. A Web Bluetooth-based user interface allows operators to access real-time water quality data on portable devices without requiring dedicated mobile apps.

The MCU also manages the system's visual and audible alert components, driving LEDs and a buzzer based on threshold exceedance conditions. Power-efficient operation is critical, and the nRF52's low-power modes and optimized BLE stack contribute to minimizing energy consumption during extended transport scenarios.

MCU / Board	Wireless	Power Consumption (Active/Sleep)	Processing Power	Pros	Cons
ESP32	Wi-Fi + BLE	150-240mA / 10-20 μ A	Dual core 240MHz	High performance, Wi-Fi + BLE	High power consumption
Nordic nRF52	BLE	5-10mA / <1 μ A	Single core 64MHz	Low power, BLE-optimized	No Wi-Fi
STM32WB55	BLE	7-15mA / <1 μ A	Dual-core 64MHz + Cortex-M0	Low power, BLE	More complex development
Texas Instruments CC2640R2F	BLE	6mA / <1 μ A	Single core 48MHz	Ultra-low power, BLE 5.0	Limited community support
Arduino (Uno, Nano)	Requires Wireless Module	50mA / No Sleep Mode	16MHz (ATmega328)	Beginner-friendly, large community	No built-in wireless, low processing power
Raspberry Pi	Wi-Fi + BLE	500mA+ / No Low Power Mode	Quad-core 1.5GHz	Powerful, full OS support	Extremely high-power consumption

Figure 3.2.1: Microcontroller Comparative Study.

3.3 Power Management

Efficient power management is a key requirement for the system, as it is intended for deployment in mobile fish transport tanks where mains power is unavailable. The system must operate reliably on battery power for at least 5 to 6 days to support typical transport durations and ensure operational flexibility.

A comprehensive power consumption analysis of all system components was performed to guide battery selection and optimization strategies. The primary contributors to power consumption are the dissolved oxygen (DO) sensor and OLED display, followed by the turbidity sensor and micro controller unit (MCU).

The system is powered by a single 18650 Li-ion cell rated at 2800 mAh, providing an operating voltage range of 3.0 V to 4.2 V. Battery charging and protection are handled by a USB-C Li-ion Charger + BMS Module (333014 IC), which includes essential safety features such as overcharge, over-discharge, and short-circuit protection. The battery is charged via a USB-C charger from a standard 110–240 V AC source. The raw battery voltage is supplied to two DC converters:

- LTC3531 converter provides a constant 3.3 V to power the nRF52 microcontroller and ICL3232 IC, MAX3485 IC, 74HC4052 IC and LCD.

- PTM23S12 DC converter boosts the voltage to 12 V to power two water-quality sensors: the Aqua Optode 4531D and the RS-ZD-N01 Renkeer Turbidity Sensor.

The raw battery rail is also monitored through a resistor divider circuit connected to the microcontroller's SAADC (Successive Approximation ADC) input pin for low battery alert functionality. This architecture ensures reliable power delivery while maintaining the flexibility and modularity of the system.

3.4 Sensors and their Interfaces

The selection of appropriate sensors is a critical component of the water quality monitoring system. The system must continuously measure three key parameters that directly affect fish welfare during transport: dissolved oxygen (DO), temperature, and turbidity. Sensor choice was guided by criteria such as measurement accuracy, long-term stability, power consumption, ease of integration with the microcontroller platform, and suitability for the constraints of a mobile transport environment.

3.4.1 Dissolved Oxygen and Temperature Sensor

For dissolved oxygen measurement, an optical luminescent DO sensor was selected due to its high accuracy, low maintenance requirements, and long operational stability. Specifically, the Aqua Optode 4531 sensor was chosen. This sensor integrates both DO and temperature measurement capabilities in a single compact unit, reducing system complexity and improving reliability.

The Aqua Optode 4531 offers an operating range of 0–1000 μM for DO with an accuracy of $<0.8 \mu\text{M}$ and a response time of less than 30 seconds. The integrated temperature sensor provides an accuracy of $\pm 0.03 \text{ }^\circ\text{C}$, with a response time of 2 seconds, and is factory-calibrated for underwater use, eliminating the need for additional temperature sensing hardware [12].

Although optical DO sensors are typically more power-intensive than galvanic or polarographic alternatives, the Aqua Optode 4531 supports power-efficient operation through adjustable sampling intervals. With a default sampling interval of 20 seconds, the sensor's average current draw is reduced to approximately 2.56 mA, making it suitable for long-duration battery-powered deployments [13].

This reports both dissolved-oxygen concentration and temperature over a serial RS-232 interface. The sensor probe is powered at 12 V and interfaced

via a MAX3232 level shifter and 74HC4052 multiplexer to the nRF52832's single UART, enabling low-power, real-time logging and alarm functionality.

3.4.2 Turbidity Sensor

The Renkeer RS485 turbidity sensor was selected for its superior accuracy, stability, and robustness. The Renkeer sensor employs a nephelometric (scattered light) measurement principle. It offers an accuracy of $\pm 5\%$, reliable performance in both low and high turbidity conditions, and long-term stability with minimal calibration requirements. Although the sensor requires a higher supply voltage (10–30 V) and uses RS485 communication, these challenges were addressed through appropriate power regulation and an RS485-to-UART interface to ensure compatibility with the nRF52 microcontroller [14].

The sensor's RS-485 output is routed through a MAX485 transceiver and a 74HC4052 multiplexer to the nRF52832's single UART, enabling seamless integration into our low-power monitoring platform.

3.4.3 Integration Challenges

Integrating both the dissolved oxygen and turbidity sensors onto a single UART port on the nRF52 DK presented a significant challenge. As an ultra-low-power microcontroller, the nRF52 DK provides only one hardware UART interface, while both sensors require UART communication. To overcome this limitation, we implemented a switching mechanism using the 74HC4052 multiplexer, allowing the microcontroller to alternate between the two data lines.

However, this solution did not fully resolve the problem. Although both sensors operated correctly when tested individually, they did not function reliably together under this shared setup due to differences in their communication behavior:

- **Automatic Data:** The Aqua Optode 4531D sends data frames automatically every 20 seconds, regardless of whether the microcontroller is actively listening. If the multiplexer is switched to the turbidity sensor at that moment, the oxygen data is missed, it is neither stored nor retransmitted.
- **On-Demand Turbidity Reads:** In contrast, the RS-ZD-N01 turbidity sensor transmits data only when explicitly requested by the microcontroller, making it much easier to manage over the multiplexer. The

microcontroller can control when to read and ensure it is listening at the right time.

Due to this mismatch, simple multiplexing was not sufficient to guarantee reliable data acquisition from both sensors. The recommended long-term solution is to configure the Aqua Optode 4531D to operate in a command-response (polled) mode, so the microcontroller can request data in a synchronized manner, similar to the turbidity sensor.

At present, due to time constraints, the system operates with both sensors connected and functional, but only one is active at a time. Each has been validated independently, and the overall architecture supports future firmware updates to enable full UART sharing once the optode is switched to polling mode.

3.5 System Diagram and Schematic

All the components mentioned above are used to design a complete system for real time monitoring, block diagram is shown in Figure 3.5.1.

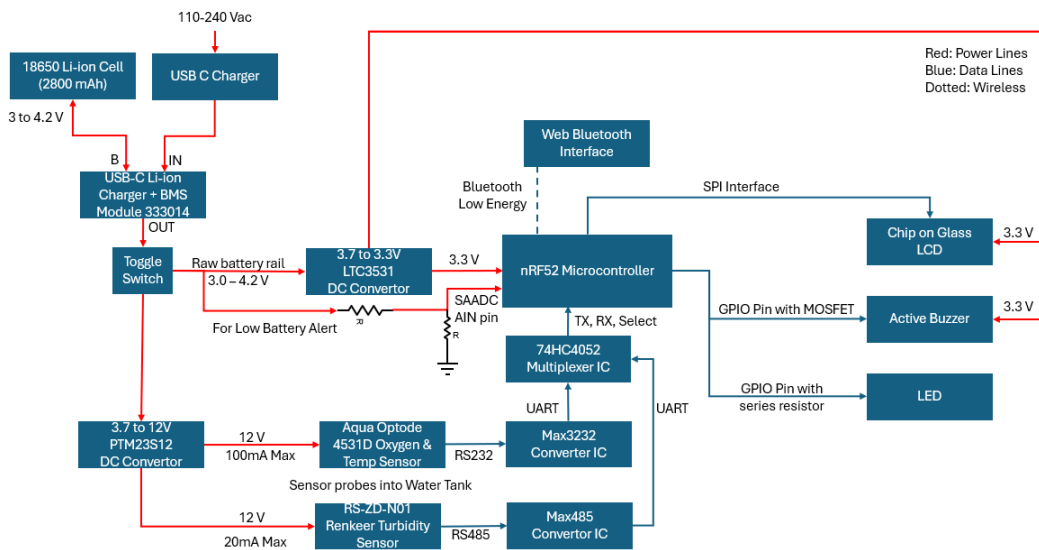


Figure 3.5.1: Block Diagram.

Our system involves communication between multiple components and their pin level integration is shown as a Schematic in Figure 3.5.2 and the circuit made on the breadboard is shown in Figure 3.5.3

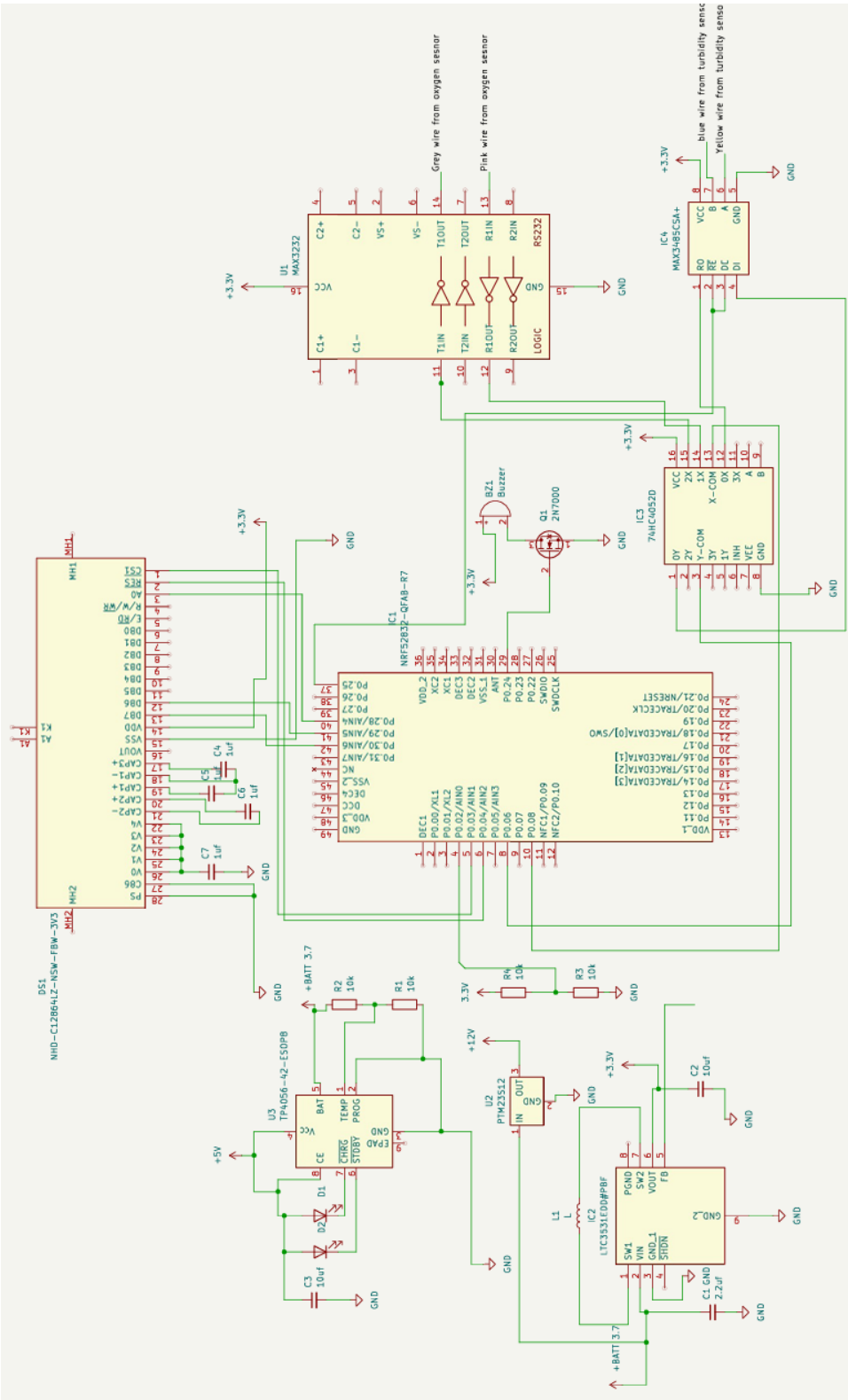


Figure 3.5.2: Schematic.

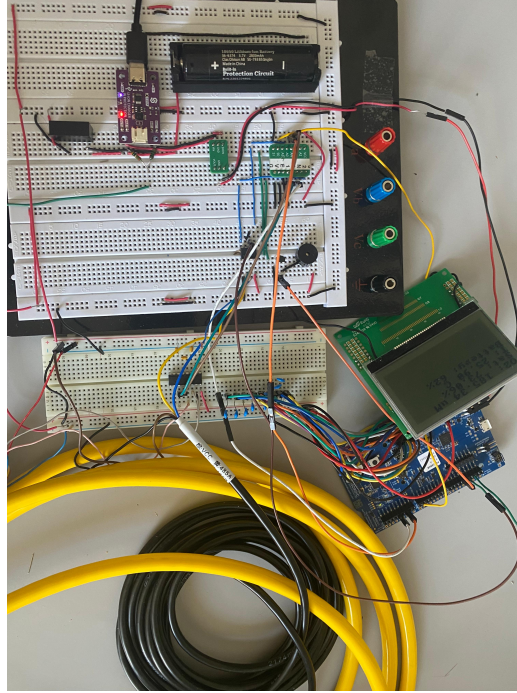


Figure 3.5.3: Circuit.

3.6 Wireless Communication

Wireless communication is a core component of the system, enabling real-time monitoring of water quality parameters from portable devices during fish transport. Given the mobile and battery-powered nature of the application, Bluetooth Low Energy (BLE) was selected over Wi-Fi, which has higher power consumption and requires continuous internet access. In the system architecture:

1. Sensors transmit data to the nRF52 microcontroller via UART interfaces.
2. The nRF52 broadcasts this data over BLE.
3. A mobile device connects via BLE and receives the data.
4. The web interface displays real-time values and allows threshold adjustments.
5. User-adjusted thresholds are sent back to the nRF52, updating its logic.

The user interface was implemented using the Web Bluetooth API, which enables direct BLE communication from a web browser without requiring a dedicated mobile application. This approach offers cross-platform compatibility and simplifies deployment in field conditions. The Web Bluetooth API allows bi-directional communication:

- The web page reads sensor data (DO, temperature, turbidity).
- The web page sends updated threshold values to the nRF52.

The interface was developed using HTML, JavaScript, and CSS, Figure 3.6.1 shows our user interface hosted on a local system.

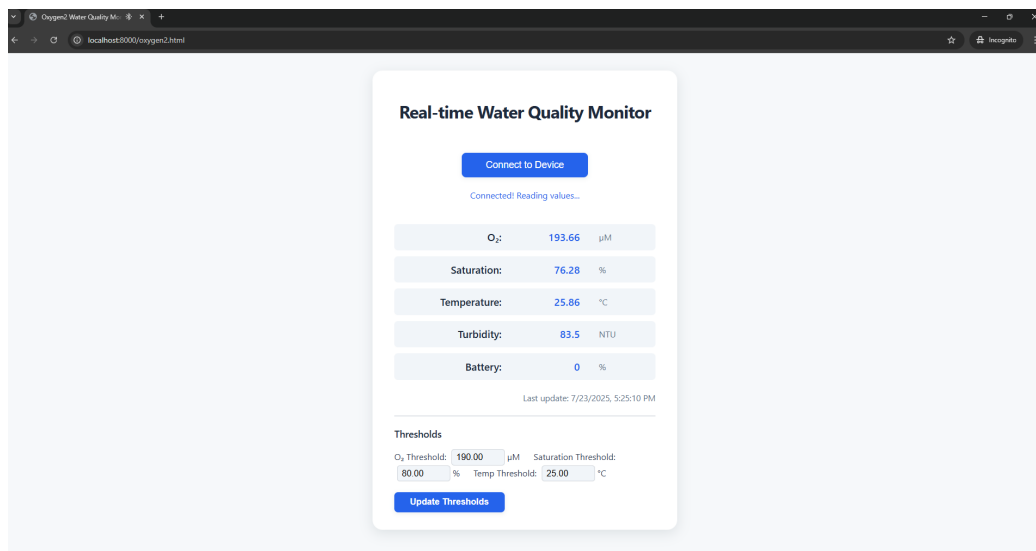


Figure 3.6.1: User Interface: Web Page

Initial BLE testing was conducted using pre-built app, nRF Connect to validate communication before implementing the Web Bluetooth-based interface. The resulting Web Bluetooth interface provides an intuitive, flexible, and low-power solution for real-time monitoring and configuration, supporting operators in maintaining optimal water quality conditions during fish transport.

3.7 Display and Alerts

In addition to wireless monitoring, the system provides local visual and audible alerts to ensure that critical water quality information remains accessible even if no mobile device is connected. This feature enhances system robustness and user safety, enabling operators to respond quickly to dangerous changes in water conditions.

3.7.1 Visual Display

A Newhaven 128 x 64 Pixels LCD display was integrated to provide real-time visualization of the current sensor values for dissolved oxygen (DO), temperature, and turbidity. The display presents data in a simple, readable format, allowing operators to monitor the tank environment at a glance.

3.7.2 Audible Alerts

The system also features a buzzer to provide immediate feedback when any water quality parameter exceeds its predefined safe threshold. The buzzer serves as an audible alarm, ensuring that operators are alerted even in noisy or visually obstructed environments.

Chapter 4

Software Implementation

This chapter details the software implementation of the system, which includes embedded firmware running on the Nordic nRF52 DK and a browser-based Web Bluetooth application. The firmware is responsible for acquiring sensor data, managing power, triggering alerts, and broadcasting readings via Bluetooth Low Energy (BLE). The web application allows users to view live sensor data and configure threshold values without requiring any mobile app installation.

The full source code for both components is available in the GitHub repository: https://github.com/MaysumAbbas/Master_Thesis

4.1 Firmware

The embedded firmware was developed on Visual Studio using the Zephyr RTOS framework, as shown in Figure 4.1.1. We used C language within the Nordic SDK environment, targeting the nRF52832 SoC. The firmware handles UART-based sensor communication, BLE GATT services, LCD updates, buzzer alerts, and ADC measurements for battery voltage.

The code is modularly organized under the `src/` directory, with each component of the system: sensors, display, and communication, encapsulated in its own source and header files. Below is an overview of the main files:

- **main.c** – Initializes peripherals, sets up the BLE server, runs the main control loop, handles multiplexer switching logic and triggers sensor reads.
- **oxygen_sensor.c / oxygen_sensor.h** – Manages communication with the Aqua Optode 4531D oxygen sensor. Parses incoming serial data (in μM and % saturation) and extracts temperature values.

- **turbidity_sensor.c / turbidity_sensor.h** – Implements Modbus RTU communication for the RS-ZD-N01 turbidity sensor. Builds query frames and parses response packets to extract NTU values.
- **lcd.c / lcd.h** – Provides functions for rendering real-time data on the NHD-C12864LZ LCD using SPI. Displays DO, saturation %, temperature, turbidity and battery voltage.
- **fonts.c / fonts.h** – Contains pixel-mapped font data used by the LCD rendering functions.
- **oxygen2.html** – A self-contained web interface for the Web Bluetooth application, allowing live sensor monitoring and threshold updates directly from the browser.
- **prj.conf** – Sets Zephyr project options, BLE stack configuration, and buffer sizes.
- **CMakeLists.txt** – Build configuration file that defines source files and build target.
- **nrf52dk_nrf52832.overlay** – Device Tree overlay that maps hardware peripherals (UART, SPI, GPIO) to physical pins on nrf52 DK.

This structured design ensures clear separation of responsibilities and supports easy future extension.

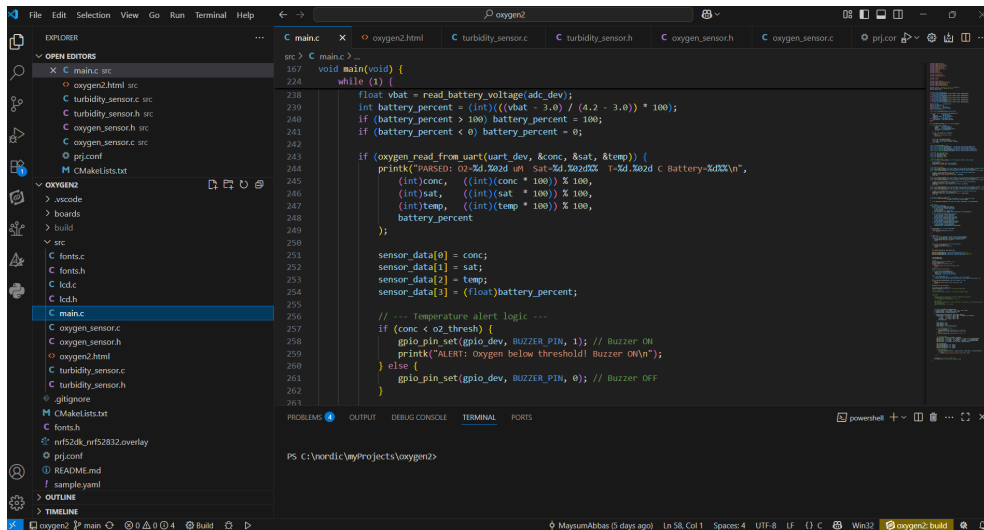


Figure 4.1.1: Screenshot of Visual Studio

4.1.1 Sensor Communication

Two UART interfaces are simulated using a single hardware UART and the 74HC4052 multiplexer. The firmware switches between the oxygen and turbidity sensor channels as needed. The switching is performed on the basis of the select SO pin on the multiplexer.

- When S0 is LOW then Turbidity sensor is selected.
- When S0 is HIGH then Oxygen sensor is selected.

The oxygen sensor currently sends data automatically every 20 seconds, while the turbidity sensor responds to Modbus requests initiated by the MCU.

For the turbidity sensor:

- A Modbus RTU request frame is constructed and sent via UART.
- The response is parsed to extract NTU values.

For the oxygen sensor:

- The UART listens passively for incoming frames.
- Frames are parsed based on known structure ("MEASUR") which appears on each readings.

4.1.2 BLE Communication

The firmware uses Nordic's BLE stack to define a custom Generic Attribute Profile GATT service with characteristics for real-time values and Threshold settings. It is a Bluetooth Low Energy (BLE) protocol that defines how data is organized and exchanged between devices.

Notifications are sent when new sensor values are available. The device advertises under the name "Oxygen2" and could be connected to any Bluetooth device. However right now it's been hosted locally only.

4.1.3 User Interface: LCD

Sensor values are displayed on a Newhaven 128x64 LCD using a custom SPI driver for the ST7565R controller. If any value exceeds its threshold, the MCU activates the buzzer. Moreover Battery voltage is periodically read using the Successive Approximation Analog-to-Digital Converter SAADC pin on nRF52 dk and displayed to the user on LCD. Figure 4.1.2 shows the LCD with the real time readings.

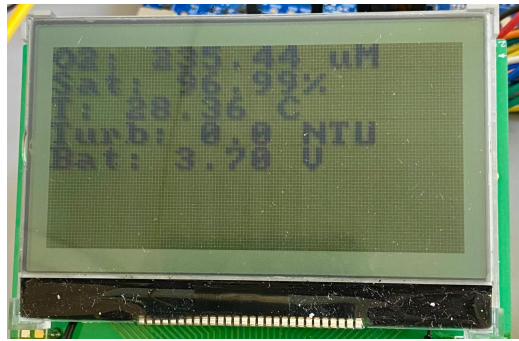


Figure 4.1.2: LCD.

4.2 Web Application

The web application is developed using HTML, JavaScript, and the Web Bluetooth API. It allows any BLE-capable browser (e.g., Chrome) to connect to the monitoring system. To run on a local server:

1. We open a terminal in the folder containing your HTML file.
2. Run: `python -m http.server 8000`
3. Visit: `http://localhost:8000/oxygen2.html`

4.2.1 Connection and Pairing

When the user clicks “Connect to Device,” the browser initiates a BLE scan and pairs with the device. Upon connection:

- The GATT service is discovered
- Sensor value characteristics are subscribed to notifications.

4.2.2 Live Data Display

The webpage dynamically updates sensor values (DO in μM , O_2 saturation in %, temperature in Celsius, turbidity in NTU) in real-time. Timestamps are shown for the last received packet.

4.2.3 Threshold Adjustment

Each parameter includes an input field for threshold configuration. When the user clicks “Update Thresholds,” new values are written to the relevant BLE characteristic on the MCU.

Chapter 5

Testing Methods

This chapter outlines the procedures used to evaluate the performance and reliability of the system under both real-world and controlled conditions. The methods cover test setups, data logging protocols, and threshold validation.

5.1 Field Simulation

To simulate a real deployment scenario, the sensor probes were placed inside a sealed black container filled with water, as shown in Figure 5.1.1. The goal was to observe how the system responds to changes in water quality under controlled but realistic conditions. The Web Bluetooth interface was used to adjust threshold values and confirm the live transmission of sensor data.



Figure 5.1.1: Test container setup with integrated sensors

5.2 Controlled Sample Testing

Two testing scenarios were used to simulate variations in water parameters:

1. **Carbonated drink (Pepsi):** Initially, the container was filled with clean tap water and baseline readings were recorded for three minutes to ensure sensor stability. A carbonated beverage (Pepsi) was then gradually added, and measurements were recorded over 10 minutes, capturing three readings per minute. This scenario simulates a low-oxygen, high-turbidity environment. The dissolved oxygen concentration, oxygen saturation (%), temperature, and turbidity values were logged from the serial monitor.
2. **Milk:** The same process was repeated by adding a few drops of milk to the tap water. This tested the turbidity sensor's sensitivity to minor changes in particle concentration and opacity.

In both cases, the following aspects were observed:

- Real-time sensor readings were verified on the Web Bluetooth UI.
- Audible alerts from the buzzer were triggered when threshold values were exceeded.
- Stability and consistency of the sensor readings were monitored.

This approach ensured that the system responded correctly to practical water quality variations and that alerts and BLE updates functioned as expected in a portable, real-time monitoring context.

Chapter 6

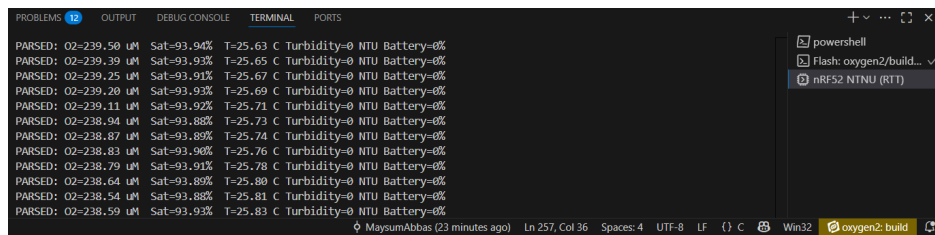
Results & Discussion

The experimental methodology was applied under controlled conditions, and the sensor system's performance was evaluated based on real-time monitoring data. This chapter presents the test outcomes and interprets the findings with respect to dissolved oxygen, oxygen saturation, temperature, and turbidity.

6.1 Sensor Readings

Figures 6.1.2 and 6.1.3 illustrate the trends in dissolved oxygen (μM), oxygen saturation (%), temperature ($^{\circ}\text{C}$), and turbidity (NTU) during the carbonated drink and milk tests, respectively. The corresponding raw data tables are provided in Appendix 8.0.2 and Appendix 8.0.1.

To demonstrate the source of these readings, Figure 6.1.1 shows a captured screenshot of the serial monitor output. Sensor values were logged via the UART interface on the nRF52 DK and parsed manually into Excel for further analysis and visualization.



The screenshot shows a serial terminal window with the following text:

```
PROBLEMS 12 OUTPUT DEBUG CONSOLE TERMINAL PORTS
PARSED: 02=239.50 uM Sat=93.94% T=25.63 C Turbidity=0 NTU Battery=0%
PARSED: 02=239.39 uM Sat=93.93% T=25.65 C Turbidity=0 NTU Battery=0%
PARSED: 02=239.25 uM Sat=93.91% T=25.67 C Turbidity=0 NTU Battery=0%
PARSED: 02=239.20 uM Sat=93.93% T=25.69 C Turbidity=0 NTU Battery=0%
PARSED: 02=239.11 uM Sat=93.92% T=25.71 C Turbidity=0 NTU Battery=0%
PARSED: 02=238.94 uM Sat=93.88% T=25.73 C Turbidity=0 NTU Battery=0%
PARSED: 02=238.87 uM Sat=93.89% T=25.74 C Turbidity=0 NTU Battery=0%
PARSED: 02=238.83 uM Sat=93.90% T=25.76 C Turbidity=0 NTU Battery=0%
PARSED: 02=238.79 uM Sat=93.91% T=25.78 C Turbidity=0 NTU Battery=0%
PARSED: 02=238.64 uM Sat=93.89% T=25.80 C Turbidity=0 NTU Battery=0%
PARSED: 02=238.54 uM Sat=93.88% T=25.81 C Turbidity=0 NTU Battery=0%
PARSED: 02=238.59 uM Sat=93.93% T=25.83 C Turbidity=0 NTU Battery=0%
```

Figure 6.1.1: Raw sensor readings captured from serial terminal during testing.

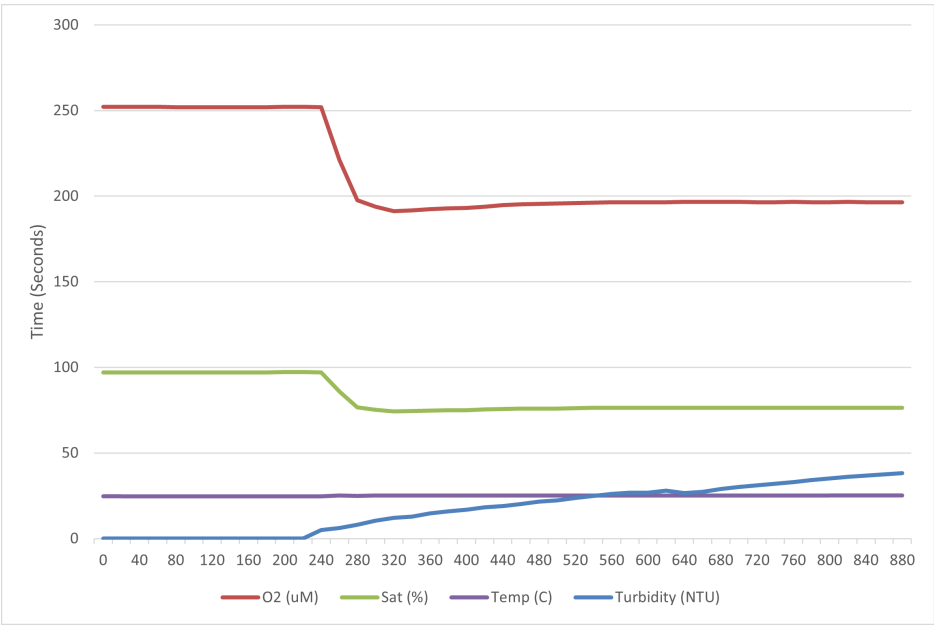


Figure 6.1.2: Sensor trends during the carbonated drink test.

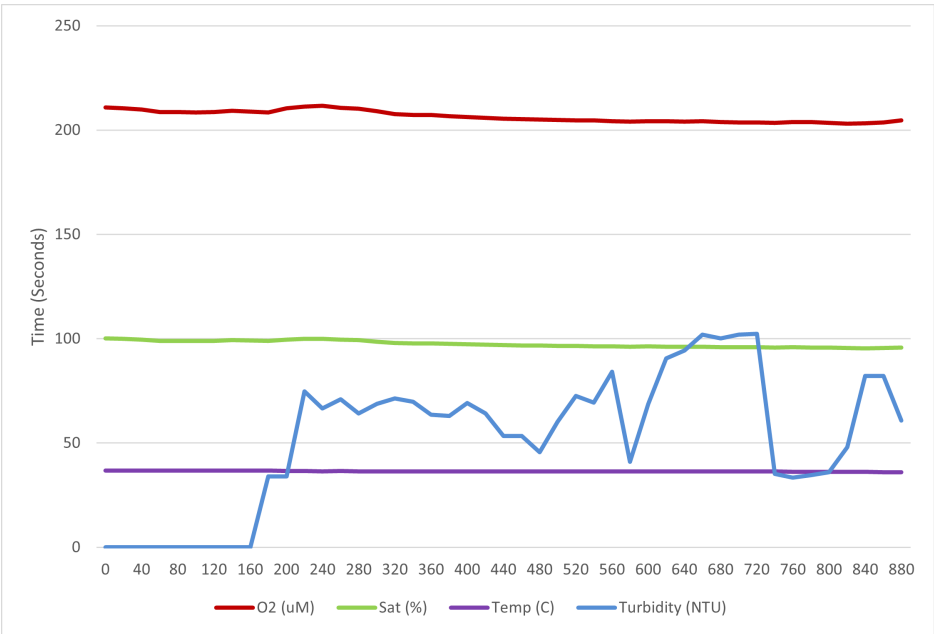


Figure 6.1.3: Sensor trends during the milk test.

6.2 Discussion

6.2.1 Sensor Performance and Parameter Trends

In the **carbonated drink test**, a significant drop in both dissolved oxygen concentration and oxygen saturation percentage was observed immediately after the drink was added to the water. This behavior is consistent with the displacement of oxygen by dissolved carbon dioxide in carbonated beverages. Meanwhile, turbidity increased steadily, simulating conditions such as fish waste or debris in transport water. The temperature remained stable throughout the test.

In the **milk test**, the dissolved oxygen and oxygen saturation remained largely unchanged. However, turbidity increased sharply due to the opaque nature of milk, mimicking situations like injury-related blood contamination in transport tanks. After an initial spike, turbidity fluctuated but showed a general upward trend, possibly due to settling dynamics. Temperature again remained constant.

These results confirm that the system accurately detects changes in critical water quality parameters in real-time. The milk test demonstrated the turbidity sensor's sensitivity to optical interference, while the carbonated drink test validated the system's capability to detect oxygen depletion scenarios.

6.2.2 Relevance to Fish Transport

The experimental simulations effectively model scenarios encountered during live fish transport. Decreases in dissolved oxygen and increases in turbidity are common stress indicators during crowded or contaminated conditions. In this context, the system successfully responded to threshold crossings and triggered local and wireless alerts.

This validates the system's potential for operational deployment in mobile aquaculture settings where timely interventions are essential to avoid fish stress or mortality.

6.2.3 Power Consumption

The system's total power consumption was estimated by analyzing both voltage rails used in the architecture: 12 V and 3.3 V.

6.2.3.1 12 V Rail:

This rail powers the Aqua Optode 4531D (DO sensor) and RS-ZD-N01 turbidity sensor.

- The turbidity sensor is only activated every 480 s (8 min), consuming approximately 1.04 mA on average [14].
- The oxygen sensor, by default configured with a sampling interval of 20 s, draws approximately 2.56 mA [13].
- With a DC-DC boost converter efficiency of 82% [15], the adjusted current draw at 12 V becomes:

$$I_{12V} = \frac{3.6 \text{ mA}}{0.82} \approx 4.39 \text{ mA}$$

- Resulting power consumption:

$$P_{12V} = 4.39 \text{ mA} \times 12 \text{ V} = 52.68 \text{ mW}$$

6.2.3.2 3.3 V Rail:

This rail supplies the nRF52 DK, level shifters (MAX3485, ICL3232), multiplexer (74HC4052), LCD module, and MOSFET driver for the buzzer.

- nRF52 DK: $\sim 5.0 \text{ mA}$ [11]
- MAX3485: $\sim 1 \text{ mA}$ [16]
- ICL3232: $\sim 0.3 \text{ mA}$ [17]
- Multiplexer: $\sim 52.8 \text{ uA}$ [18]
- LCD: $\sim 0.5 \text{ mA}$ [19]
- Total current: 6.85 mA
- Power consumption:

$$P_{3.3V} = 6.85 \text{ mA} \times 3.3 \text{ V} = 22.6 \text{ mW}$$

6.2.3.3 Total System Power & Runtime:

The total power consumption is calculated as the sum of both voltage rails:

$$P_{total} = P_{12V} + P_{3.3V} = 75.28 \text{ mW}$$

Battery Life Estimation: The system uses a 18650 Li-ion cell rated at 2800 mAh and a nominal voltage of 3.7 V.

$$E = 2.8 \text{ Ah} \times 3.7 \text{ V} = 10.36 \text{ Wh}$$

$$\text{Estimated Runtime} = \frac{10.36 \text{ Wh}}{0.07528 \text{ W}} \approx 137.6 \text{ hours} \approx 5.73 \text{ days}$$

This estimate validates that the system can run for nearly 6 days on a single charge, aligning well with typical fish transport durations.

Chapter 7

Conclusion & Future Work

This thesis presented the design, implementation, and evaluation of a low-power, real-time water quality monitoring system tailored for live fish transport. The system integrates commercial oxygen and turbidity sensors, a Nordic nRF52 BLE-enabled microcontroller, and a dual-interface display (local LCD and Web Bluetooth) to support both on-site and wireless interaction.

7.1 Summary of Contributions

- Developed a compact and modular hardware platform that integrates both RS-232 and RS-485 sensors through a single UART interface using a multiplexer.
- Implemented low-power firmware featuring BLE communication and visual/audible alerts based on threshold exceedance.
- Designed and tested a browser-based Web Bluetooth interface for real-time data access and threshold configuration without the need for dedicated apps.
- Validated the system's performance through controlled experiments simulating realistic fish transport scenarios.
- Demonstrated a battery runtime exceeding five days on a single 18650 Li-ion cell, supporting typical short to mid-duration fish transport operations.

7.2 Limitations and Future Work

- The oxygen sensor currently operates in automatic (broadcast) mode, which complicates reliable multiplexed UART access. Reconfiguring it to command-response (polled) mode as documented in its datasheet would resolve this limitation, though this step was not completed due to time constraints.
- Additional power savings could be achieved by optimizing sleep modes in the firmware and reducing the LCD refresh rate.
- The system has only been tested under controlled laboratory conditions. Field trials during actual fish transport are needed to evaluate robustness and reliability in dynamic environments.
- Potential future upgrades include support for additional sensors (e.g., pH or ammonia), cloud-based data logging, and integration with actuators such as automated aerators or oxygen injectors.
- The current prototype should be housed in an IP66-rated waterproof enclosure to ensure environmental protection for real-world deployment.
- The Web Bluetooth interface is currently hosted locally; future work may involve deploying it on a publicly accessible web server to allow broader access and remote monitoring.

7.3 Final Remarks

This work demonstrates the feasibility of a lightweight, low-power, and cost-effective solution for real-time monitoring of water quality during fish transport. By leveraging commercially available sensors and energy-efficient embedded design, the system provides a practical foundation for enhancing aquaculture logistics and safeguarding aquatic animal welfare in transit.

7.4 Declarations

The following declarations are made regarding the tools, platforms, and support systems used throughout the development of this thesis project:

1. **Circuit Design:** All circuit schematics were designed using KiCAD, an open-source PCB design and simulation tool. It was used to visualize component-level connections and generate accurate electrical schematics for the system.
2. **Diagram and Documentation Graphics:** Block diagrams and system overviews were created using Canva and Microsoft PowerPoint. These tools enabled helped to present hardware architecture, signal flow, and user interface concepts in a clear and visually engaging manner.
3. **Embedded Firmware Development:** The firmware for the monitoring system was written in C using Visual Studio Code, with the Nordic Semiconductor's nRF Connect SDK as the development framework. The target platform was the nRF52832 microcontroller, programmed and debugged using the nRF52 Development Kit and the nRF Command Line Tools.
4. **Language and Documentation Assistance:** ChatGPT by OpenAI was used to assist with improving the clarity, technical tone, and grammatical correctness of the written documentation. Also its assistance were taken in writing the code.

Chapter 8

Appendices

Code is uploaded to the Github repository. Below is a link to a Github repository for this project:

Github repository link

- https://github.com/MaysumAbbas/Master_Thesis.git

Sensor Readings: Milk Test

Time (s)	O2 (uM)	Sat (%)	Temp (C)	Turbidity (NTU)
0	210.94	100.05	36.77	0
20	210.41	99.84	36.79	0
40	209.79	99.48	36.75	0
60	208.67	99.03	36.8	0
80	208.66	99.01	36.79	0
100	208.51	98.94	36.79	0
120	208.61	99.01	36.8	0
140	209.32	99.31	36.78	0
160	208.86	99.07	36.77	0
180	208.43	98.91	36.8	33.9
200	210.41	99.54	36.6	33.9
220	211.35	99.93	36.57	74.8
240	211.6	99.88	36.47	66.5
260	210.74	99.53	36.5	71
280	210.3	99.26	36.47	64.2
300	209.02	98.63	36.45	68.8
320	207.64	97.97	36.44	71.4
340	207.22	97.78	36.44	69.7
360	207.17	97.72	36.42	63.6
380	206.69	97.5	36.43	63
400	206.29	97.3	36.41	69.1
420	205.94	97.11	36.41	64.1
440	205.42	96.87	36.41	53.3
460	205.21	96.75	36.4	53.4
480	205.07	96.7	36.4	45.6
500	204.92	96.61	36.39	60.2
520	204.76	96.53	36.39	72.5
540	204.59	96.44	36.38	69.4
560	204.3	96.29	36.37	84.1
580	204.16	96.22	36.37	40.9
600	204.29	96.27	36.36	68.7
620	204.2	96.22	36.36	90.5
640	204.06	96.14	36.35	94.3
660	204.24	96.21	36.34	102
680	203.88	96.04	36.34	100.1
700	203.65	95.92	36.33	101.9
720	203.64	95.88	36.31	102.4
740	203.54	95.82	36.3	35.1
760	203.85	95.88	36.25	33.4
780	203.91	95.81	36.18	34.6
800	203.5	95.65	36.2	35.9
820	203.15	95.47	36.19	48
840	203.21	95.41	36.14	82.2
860	203.74	95.52	36.05	82.2
880	204.59	95.77	35.95	60.7

Figure 8.0.1: Recorded oxygen, saturation, temperature, and turbidity values during milk test.

Sensor Readings: Carbonated Water Test

Time (s)	O2 (uM)	Sat (%)	Temp (C)	Turbidity (NTU)
0	252.13	97.14	24.66	0
20	252.14	97.15	24.66	0
40	252.1	97.14	24.67	0
60	252.08	97.14	24.67	0
80	252.04	97.13	24.67	0
100	251.89	97.07	24.67	0
120	251.94	97.09	24.67	0
140	251.93	97.09	24.68	0
160	251.84	97.06	24.68	0
180	251.83	97.06	24.68	0
200	252.08	97.16	24.68	0
220	252.24	97.23	24.69	0
240	251.89	97.1	24.69	5.1
260	221	85.81	25.08	6.1
280	197.62	76.65	25.03	8
300	193.78	75.19	25.04	10.4
320	191.12	74.19	25.07	12
340	191.64	74.4	25.07	12.8
360	192.46	74.73	25.08	14.6
380	192.87	74.91	25.09	15.9
400	193.18	75.04	25.1	16.9
420	193.92	75.33	25.1	18.2
440	194.66	75.62	25.11	19.1
460	195.19	75.84	25.11	20.2
480	195.45	75.94	25.12	21.5
500	195.61	76.01	25.12	22.3
520	195.95	76.15	25.13	23.8
540	196.3	76.29	25.13	25
560	196.44	76.35	25.13	26
580	196.43	76.35	25.13	26.8
600	196.37	76.32	25.14	26.8
620	196.51	76.38	25.14	28
640	196.64	76.44	25.14	26.5
660	196.57	76.41	25.14	27.4
680	196.66	76.45	25.14	29
700	196.63	76.44	25.15	30.2
720	196.54	76.41	25.15	31.1
740	196.54	76.41	25.15	32
760	196.55	76.42	25.15	33
780	196.48	76.39	25.15	34.1
800	196.51	76.41	25.16	35.1
820	196.55	76.42	25.16	36.1
840	196.5	76.4	25.16	36.7
860	196.52	76.41	25.16	37.5
880	196.54	76.42	25.16	38.2

Figure 8.0.2: Recorded oxygen, saturation, temperature, and turbidity values during carbonated water test.

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