ECE 445 - Senior Design Lab

Design Document

**Automatic Water Quality Monitoring using Test Strips**

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March 5th, 2025

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# Introduction

## Problem

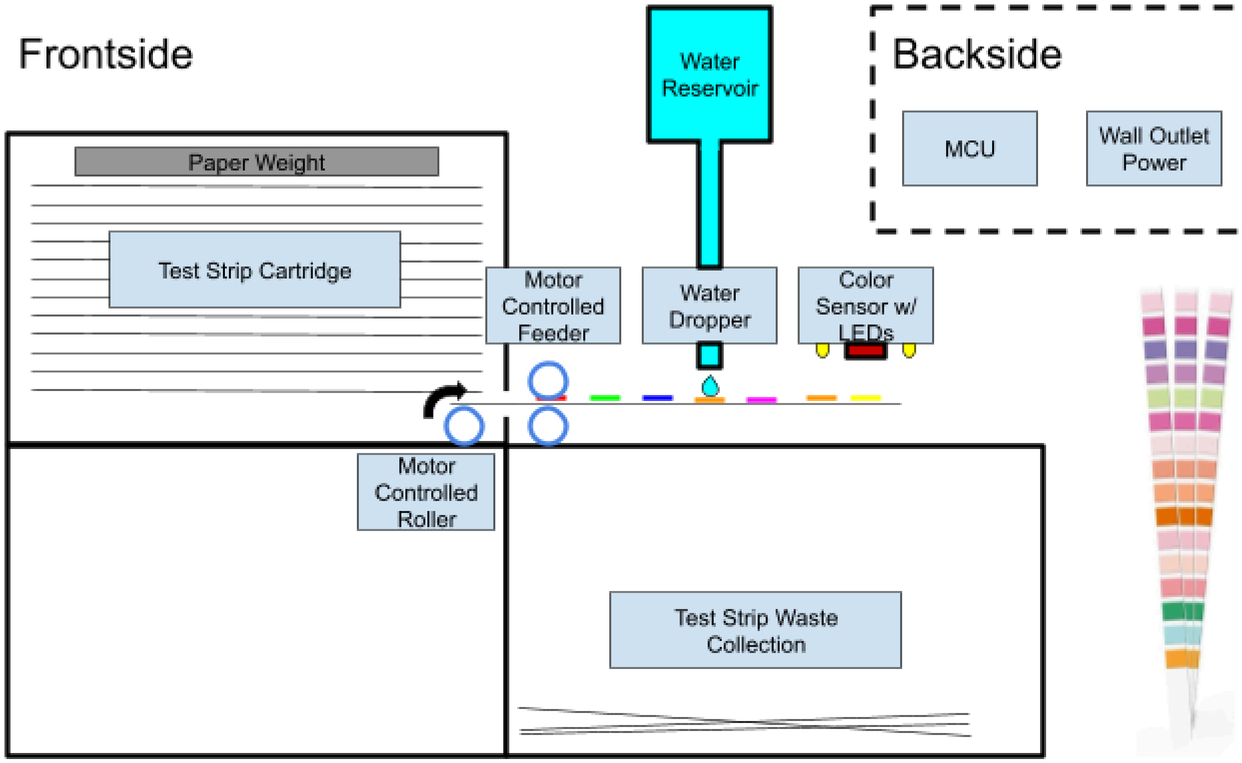
Water quality testing is recommended by the Environmental Protection Agency (EPA) for ensuring safe water consumption and alerts to poor water quality in homes and industrial settings [1]. Frequent water testing can provide human owners with early warnings of water crises such as lead contamination in Flint, Michigan [2]. Traditionally, getting accurate measurements relies on lab-controlled testing with specialized equipment [3]. Due to their high cost, lab testing is mainly reserved for industrial applications and options for at-home testing include digital measurement devices and, most commonly, chemically reactive paper test strips. These test strips react chemically with water samples, requiring users to manually interpret color changes against reference charts. This method is time-consuming and susceptible to human error due to variations in lighting conditions and subjective color interpretation. While digital alternatives exist for some tests, such as pH meters, they tend to be expensive, require calibration, and do not support a wide range of compound and elemental tests. This gap highlights the need for an automated system capable of handling multiple test strip types, standardizing the testing process, and improving accuracy. However, test strips are significantly less expensive and can measure more substances than digital measurement devices. Designing a hardware system to streamline the testing process provides frequent automated testing with higher accuracy, providing and storing results for users, and creating safer home environments.

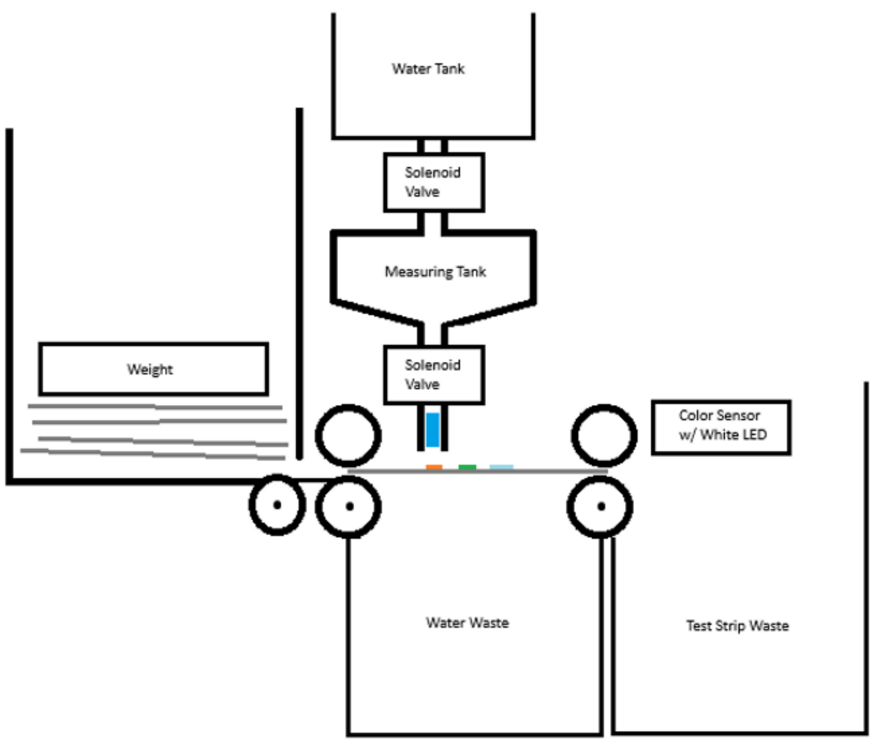
## Solution

Our proposed solution is an automated water quality monitoring system that utilizes traditional testing strips to eliminate manual effort and remove the effects of human perceptual error. The system consists of a fully enclosed mechanism designed to dispense water onto test strips, wait for the chemical reactions to complete, and accurately read the color changes using optical color sensors or a digital camera. Our test strip of choice contains 16 different chemical pads shown in the visual aid below which contain measurements for Nitrate, Nitrite, Total Hardness, Free Chlorine, Total Chlorine, Bromine, MPS, Copper, Iron, Lead, Nickel, Sulfite, Cyanuric Acid, Carbonate, Total Alkalinity, and pH with concentrations measured in parts per million (ppm) measured on different scales and colors for each substance. Each test pad will be tested sequentially and given the recommended 30 seconds to react before the color is read. Doing this sequentially also mitigates the problem of the test strip color fading from waiting too long while reading the colors.

The system will feature an automated feeder mechanism that retrieves test strips from a storage cartridge, a precise water dispensing system, an integrated color analysis module, and a used test strip collection system for the user to dispose of. Results will be displayed on a monitor or transmitted to a host system. This approach ensures consistency, accuracy, and efficiency while maintaining affordability by using widely available test strips instead of expensive digital sensors. By using a color sensing system with LEDs to control lighting conditions, we can further decrease environmental factors.

Visual Aid


Frontside
Water Reservoir
Backside
MCU
Wall Outlet Power
Paper Weight
Test Strip Cartridge
Motor Controlled Feeder
Water Dropper
Color Sensor w/ LEDs
Motor Controlled Roller
Test Strip Waste Collection


Water Tank
Solenoid Valve
Measuring Tank
Weight
Solenoid Valve
Color Sensor w/ White LED
Water Waste
Test Strip Waste

## High-level Requirements List

- The system must automatically dispense a fresh test strip, apply water to fully saturate the test strip, and read the color change without human intervention at least once per testing cycle.

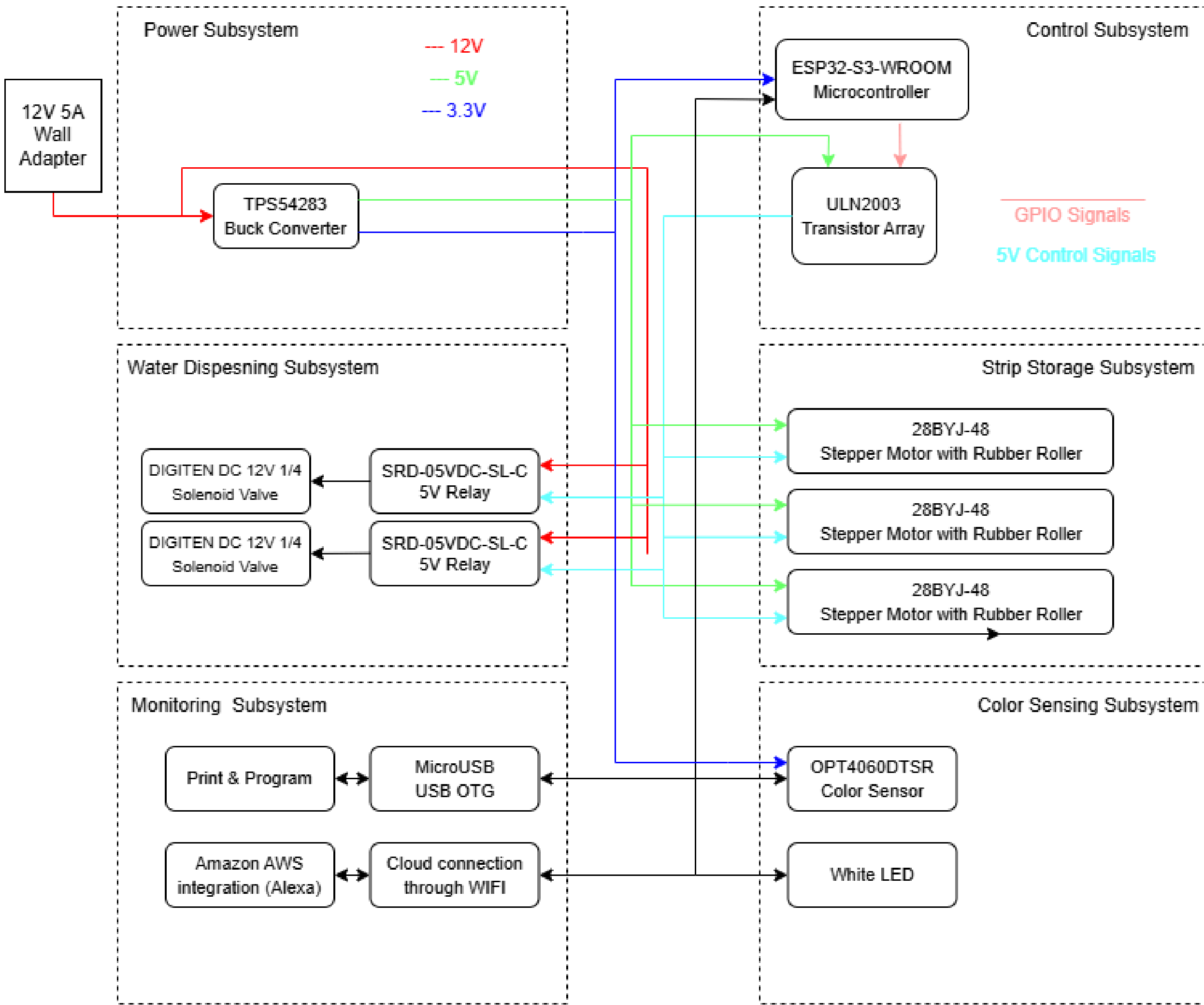
- The color detection module must be capable of analyzing the test strip with an accuracy of at least 80% compared to a human observer under controlled lighting conditions.

- The feeder system must accurately place the test strip under the water dispenser system and subsequently the color sensing system within (± 5mm).

- The system must be able to consistently output the same measurements using the same water sample when run over multiple test runs. The measurements must be within 10% accuracy of their average.

# Design

## Block Diagram



# Subsystem Overview and Requirements

## Subsystem 1: Water Dispensing Subsystem

**Overview:**

The water dispensing subsystem is responsible for delivering a precise amount of water onto the entire test strip inside the water chamber. It is made up of a water tank, two solenoid valves, and a measuring pipe. The water tank will be positioned above the water dispensing chamber to utilize gravity and allow water to flow without a pump. Using a set of two solenoid valves, we allow water to fill up the measuring pipe to obtain a consistent function for flow rate regardless of how much water is in the water tank. This way the flow rate would be a function in terms of time and a constant "V" which is the volume of the middle measuring pipe, which acts as a measuring tank.

The solenoid valves we will use is the "DIGITEN DC 12V 1/4"" which will use power from the main 12V power source and through the use of a relay (SRD-05VDC-SL-C) and a transistor array (ULN2003), the microcontroller directly controls the relays to open and close the two valves.

Once water has been applied, the strip advances through the system for analysis. The dispensing mechanism interacts with the strip storage subsystem to ensure water is applied at the correct stage. It receives control signals from the control unit to precisely regulate the amount of water dispensed, ensuring uniform coverage.

**Requirements and Verification**

| Requirement | Verification Procedure |
| --- | --- |
| The water dispensing subsystem must deliver 1 mL ± 0.5 mL of water per test strip square application. | • Connect the solenoid valve to a water source and a power supply.<br>• Activate the solenoid for a controlled |

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| | duration using the microcontroller.<br>● Dispense the water onto a scale and measure the mass of the dispensed water. over 10 different trails.<br>● Convert mass to volume (1g = 1ml).<br>● Verify that at least %90 of trails fall within the 1 mL ± 0.5 mL range. |
| The subsystem must prevent leakage or excessive water flow beyond the designated amount. | ● Visually inspect the solenoid valve for any leaks after activation and deactivation.<br>● Run a dry test where the solenoid is powered without dispensing to check for unintentional drips.<br>● Verify that leakage does not exceed 1 mL per cycle when the solenoid is inactive. |
| The water dispensing must complete the application within 5 seconds after receiving a control signal. | ● Send a digital trigger signal from the control unit to the solenoid.<br>● Measure the time delay from signal activation to water dispensing using an oscilloscope or a high-speed camera.<br>● Ensure the response time is within the 5-second limit in at least 90% of trials. |
| The subsystem must coordinate with the strip positioning system to ensure water is applied at the correct stage. | ● Activate the strip feeder motor and the solenoid in sequence according to the control unit logic<br>● Confirm that the strip is stationary before the water is dispensed<br>● Perform 10 trials and verify that water is dispensed only when the strip is in position at least 90% of trials. |

## Subsystem 2: Strip Storage Subsystem

**Overview:**

The strip storage and positioning subsystem holds, feeds, and accurately moves the paper strip through the testing process. The strips are arranged horizontally on top of each other, with a motorized roller mechanism that pushes one strip at a time into the water chamber. A feeder stepper motor advances the strip through the system while ensuring each square is properly positioned for testing.

The storage chamber consists of a rubber roller connected to a stepper motor shaft (28BYJ-48), and a piece of weight used to ensure the bottom strip has enough friction with the roller. The walls of the chamber itself are used to ensure that only the bottommost strip gets fed into the cycle.

After the strip is fed, a pincher consisting of a motor driven rubber roller paired with an idle rubber roller catches the strip and starts moving it in small steps under the water dispenser. A roller is added midway through the water dispensing chamber to stop the strip from bending down, then another pincher continues the cycle with small steps under the color sensor system, which at the end drops it in the test strip waste basket.

**Requirements and Verification**

| **Requirement** | **Verification Procedure** |
|---|---|
| The subsystem must reliably dispense one strip at a time from the storage stack with 90% accuracy. | • Load a stack of test strips into the storage compartment.<br>• Activate the strip feeder mechanism 10 times.<br>• Verify that only one strip is dispensed per activation in at least %90 of trials. |
| The feeder motor must advance the strip to the water chamber within 3 seconds of receiving a control signal. | • Send a digital trigger signal from the control unit to activate the feeder motor.<br>• Measure the time taken for the strip to reach the water chamber using a stopwatch or camera. |

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| | ● Verify that the strip reaches the chamber within 3 seconds in at least 90% of trials. |
| The subsystem must position the test strip within ±0.5 cm of the intended position before dispensing water. | ● Mark the target position on the strip feeder path.<br>● Activate the feeder motor and measure the stopping position of the strip using a caliper or ruler.<br>● Conduct 10 trials and ensure that at least 9 out of 10 trials result in the strip being within ±0.5 cm of the target. |
| The second roller must hold the strip in place during testing to prevent movement. | ● Activate the system and dispense water onto the strip.<br>● Observe whether the strip remains stable without shifting.<br>● Conduct 10 trials and ensure that at least %90 of trials show no unwanted strip movement. |
| After testing, the strip must be moved to the waste collection area within 5 seconds after the final sensor reading. | ● Activate the test sequence and allow the strip to proceed through water dispensing and color sensing.<br>● Measure the time taken for the strip to be fully ejected into the waste collection area after final analysis.<br>● Verify that the process is completed within 5 seconds in at least 90% of trials. |

## Subsystem 3: Power Subsystem

**Overview:**

The power subsystem supplies consistent and reliable power to all other subsystems. A 12V 5A Wall adapter plug supplies power through a barrel jack connector. The 12 V is then used as a 12V railing (for the solenoids) and is also turned down using the TPS54283 dual channel buck converter. The buck converter outputs 3.3V and 5V with a maximum of 2A per channel, which should be enough for our needs.

The power system also includes relays for the solenoid valves, and a transistor array (ULN2003) which is used to allow the ESP-32 microcontroller to control the 5V relay and the 5V stepper motors; the transistor array is required since the ESP-32 can only output a high signal of 3.3V

| **Requirement** | **Verification Procedure** |
| --- | --- |
| The power subsystem must be able to supply at least 800mA per voltage railing (12V, 5V, 3.3V) continuously to the rest of the system. | ● Use a multimeter to measure the current draw from each voltage rail under full system load.<br>● Verify that each rail (12V, 5V, 3.3V) can supply at least 800mA without causing voltage drops or instability. |
| The subsystem must reliably convert 12V power to 3.3V and 5V for the system's components. | ● Measure the output voltages of the TPS54283 buck converter under load conditions.<br>● Ensure that the output voltages are stable at 3.3V and 5V within ±5% tolerance.<br>● Verify that there is no significant voltage ripple or noise that could affect subsystem operation. |
| The system must include overcurrent protection and short circuit protection. | ● Use a power supply with adjustable current limiting to simulate an overcurrent scenario.<br>● Measure whether the system properly shuts down or reduces current supply when it exceeds the safe current limits (e.g., 1.2A for 5V rail).<br>● Short each output rail momentarily and |

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| | ensure the system either shuts down or triggers the protection mechanism to prevent damage. |
| The power subsystem must ensure stable operation even during sudden power fluctuations or voltage drops. | ● Introduce a simulated voltage drop or surge in the 12V input using an adjustable power supply.<br>● Monitor the stability of the 5V and 3.3V outputs using an oscilloscope.<br>● Ensure the output voltages do not drop below their required thresholds for more than 1 second. |

## Subsystem 4: Control Unit

**Overview:**

The control unit, based on the ESP32-S3-WROOM-1-N8 [9] microcontroller, serves as the brain of the system, coordinating all subsystems. It communicates with the color sensing subsystem via I2C, sends control signals to the water dispensing and strip storage subsystems through the transistor array and relays, and transmits processed data to the monitoring subsystem. It also receives input from an override button to allow manual operation if necessary.

**Requirements and Verification**

| **Requirement** | **Verification Procedure** |
|---|---|
| The control unit must send a signal to activate the water dispensing subsystem within 2 seconds after the strip reaches the correct position. | ● Place a test strip in the system and trigger the movement sequence.<br>● Measure the time delay between the strip reaching its position and the activation signal being sent to the solenoid valve using an oscilloscope or timestamped logs.<br>● Verify that the signal is sent within 1 second in at least 90% of trials. |
| The control unit must correctly coordinate the strip movement, water dispensing, and color sensing subsystems in the correct sequence 90% of the time. | ● Run the system through 10 complete test cycles.<br>● Observe if each subsystem is triggered at the correct time: (1) strip advances, (2) strip stops, (3) water dispenses, (4) strip moves under the sensor, (5) strip is discarded.<br>● Verify that all subsystems follow the correct order in at least 90% of the trials. |
| The control unit must process and transmit sensor data within 2 seconds after water is dispensed. | ● Inject a test input into the color sensor and trigger a reading.<br>● Measure the time between water dispensing and when processed data is sent to the monitoring subsystem.<br>● Verify that data is transmitted within 2 seconds in at least 90% of trials. |
| The control unit must store and log at least 50 test | ● Run the system through 50 full test cycles. |

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| results for later analysis. | <ul><li>Access the stored data and verify that each test result is recorded and retrievable.</li><li>Ensure no test results are missing or overwritten prematurely.</li></ul> |
| The system must allow manual override via a physical button, which must respond within 2 second of being pressed. | <ul><li>Press the manual override button while the system is running.</li><li>Measure the time taken for the control unit to halt operations using a timestamped event log or oscilloscope.</li><li>Verify that the system halts within 1 second in at least 90% of trials.</li></ul> |

## Subsystem (Extra Credit): Color Sensing Subsystem

**Overview:**

This subsystem detects the color changes on the test strip to determine water quality. It comprises an RGB color sensor (OPT4060DTSR) [5] with controlled white LED lighting to ensure consistent and accurate readings. The data collected from this subsystem is processed and compared against predefined color values to determine chemical concentrations. It interfaces with the monitoring subsystem to display results and connects to the control unit via I2C for data transmission.

**Requirements and Verification**

| Requirement | Verification Procedure |
| --- | --- |
| The color sensing subsystem must detect and classify color changes on the test strip with an accuracy of at least 95% when compared to a human observer. | ● Place a test strip with known reference colors under the sensor.<br>● Capture the sensor's RGB or LAB readings and compare them to expected reference values.<br>● Verify that the system correctly identifies colors with 90% accuracy |
| The subsystem must capture and process color data within 2 seconds after the strip is positioned under the sensor. | ● Trigger the strip movement to position it under the color sensor.<br>● Measure the time between strip positioning and color data availability.<br>● Verify that the system processes and outputs color data within 2 seconds in at least 90% of trials. |
| The system must use consistent lighting (via white LEDs) to ensure accurate color readings, with illumination variation below ±10%. | ● Measure LED brightness using a light meter at the sensor's position.<br>● Ensure variations in light intensity remain within ±10% across multiple tests.<br>● Verify that sensor readings remain stable under different lighting conditions. |
| The color sensor must correctly differentiate between at least six distinct color shades that correspond to different chemical concentrations. | ● Test the system using test strips with known chemical concentrations.<br>● Compare the sensor's detected color values to expected color chart data.<br>● Verify that at least six different color shades are consistently recognized. |
| The sensor must interface with the control unit via I2C communication, ensuring data transmission success at least 95% of the time. | ● Establish communication between the color sensor and the control unit via I2C.<br>● Send 100 test commands and verify that |

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| | data is received without transmission errors.<br>● Confirm that successful data transmission occurs in at least 95% of trials. |

## Subsystem (Extra Credit): Monitoring Subsystem

**Overview:**

This subsystem processes and displays the test results. It consists of a microcontroller that reads data from the color-sensing subsystem and translates it into meaningful water quality metrics. The results can be displayed through WiFi to a smart home app. We will use Amazon Alexa for our smart home app connection. The results will also be transmitted via a Micro USB plug, using the ESP32 USB OTG pin, to an external host device for logging and further analysis. Additionally, an override button allows manual intervention if needed.

**Requirements and Verification**

| **Requirement** | **Verification Procedure** |
|---|---|
| The monitoring subsystem must display test results through USB and WiFi within 3 seconds after data is received from the control unit. | ● Trigger a full test cycle and capture sensor data.<br>● Measure the time between when data is received and when the test result is displayed.<br>● Verify that results appear within 3 seconds in at least 90% of trials. |
| The monitoring subsystem must correctly receive and log test results for at least 50 test cycles without data loss. | ● Run the system for 50 complete test cycles.<br>● Retrieve the stored test data and verify that all 50 results are accurately recorded.<br>● Ensure that no test results are missing or duplicated. |
| The system must be capable of transmitting stored test results via USB or wireless communication to an external device. | ● Connect the monitoring system to a computer via USB or wireless interface.<br>● Send a command to retrieve stored test results.<br>● Verify that the received data matches the stored results and is transmitted successfully in %90 of the trials. |
| The system must indicate when a test fails due to | ● Intentionally introduce an error (e.g., |

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| an error (e.g., improper water application, misalignment of strip). | misaligned strip or incorrect water volume).<br>● Observe if the monitoring system detects the error and displays an appropriate warning message.<br>● Verify that an error message is displayed in 90% of cases where errors occur. |

# Tolerance Analysis

One of the most critical aspects of our design is ensuring precise strip positioning and accurate water dispensing to maintain consistent test results. Any misalignment or variation in water volume could impact the reliability of the chemical reaction. To validate our system, we analyze key performance tolerances through mathematical modeling and experimental validation.

The strip positioning subsystem must align each test square within ±0.5 cm of the center to ensure correct water application. The stepper motor moves the strip in discrete steps, where displacement per step is given by:

$$D = C/N$$

where D is the displacement per step, C is the roller circumference, and N is the step count per revolution. To meet accuracy requirements, we will calibrate motor movement and verify positioning using optical sensors. The system must also stop the strip at four designated positions at least 90% of the time, which will be optimized by refining acceleration and braking profiles.

The water dispensing subsystem must deliver 1 ml ± 0.5 ml of water per square, ensuring precise solenoid control. Variations in solenoid timing, water pressure, and flow rate introduce uncertainty, which we will address through calibration. By testing multiple dispensing cycles and measuring output with a high-precision scale, we aim to achieve 90% accuracy in dispensing.

Finally, the entire testing process must be completed within 1 minute at least 90% of the time. The total cycle time is modeled as:

$$T = T_{positioning} + T_{dispensing} + T_{processing}$$

where each component contributes to overall efficiency. If testing exceeds the time limit, optimizations such as increasing stepper motor speed, reducing solenoid response lag, or parallelizing operations will be implemented.

By combining stepper motor calibration, solenoid timing adjustments, and iterative testing, we will refine system performance to meet accuracy and timing requirements.

# Cost and Schedule

## Cost Analysis

**Labor Costs**

For labor calculations, we assume an average hourly salary of $40/hour for an Electrical and Computer Engineering (ECE) graduate from UIUC—the 2.5x multiplier accounts for overhead and benefits.

Assumptions:

- Estimated total work hours per team member: 150 hours
- Number of team members: 2

Labor cost per person:

40 (hourly wage) × 2.5 × 150 = $15,000

Total labor cost for the team:

15,000 × 2 = $30,000

**Component Cost Breakdown**

| **Component** | **Quantity** | **Estimated Cost (per unit)** | **Total Cost** |
|---|---|---|---|
| Molex 1050170001 MicroUSB Port | 1 | $0.83 | $0.83 |
| RAPC722X Barrel Jack Adapter | 1 | $2.34 | $2.34 |
| ESP32-S3-WROOM-1U-N8 Microcontroller | 1 | $4.95 | $4.95 |
| TPS54283PWPR Dual-Channel Buck Converter | 1 | $2.96 | $2.96 |
| ULN2003ADR Transistor Array | 3 | $0.55 | $1.65 |
| ROCON-341 Solenoid Valve (DIGITEN 12V ¼”) | 2 | $7.49 | $14.98 |
| 28BYJ-48 Stepper Motor (3 Pack) | 1 | $14.99 | $14.99 |
| 12V 5A Wall Adapter to Barrel Jack | 1 | $11.11 | $11.11 |

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|---|---|---|---|
| OPT4060DTSR Color Sensor | 1 | $2.80 | $2.80 |

**Total Component Cost: $53.67**
**Final Estimated Project Cost: $30,053.67**

## Schedule

Below is a structured schedule detailing the major milestones and task assignments for the project. Tasks are distributed among team members based on their roles, ensuring an efficient workflow.

**Week-by-Week Breakdown**

| Week | Milestone | Task Assignment |
|---|---|---|
| **3/10** | **Breadboard Demonstration & Second PCB Order** | Assemble breadboard prototype, test strip positioning system, implement basic control logic for strip movement, validate solenoid valve water dispensing. |
| **3/17** | **Spring Break** | No scheduled tasks (Optional: research improvements, refine design plans). |
| **3/24** | **Finalize PCB Design & Order Parts** | Refine circuit designs based on breadboard results, confirm microcontroller code integration, order necessary components. |
| **3/31** | **Third PCB Order & Individual Progress Reports** | Debug and refine strip positioning accuracy, improve water dispensing precision, integrate and test sensor readings. Submit individual reports. |
| **4/7** | **Fourth PCB Order & Begin Assembly** | Assemble final PCBs, integrate system components, refine motor and sensor synchronization. |
| **4/14** | **Full System Integration & Testing** | Calibrate water dispensing volume and strip movement, refine data processing and monitoring display, test full cycle automation. |
| **4/21** | **Mock Demo with TA & Debugging** | Perform dry run of the full system, debug any mechanical or software issues, ensure reliability of test strip positioning. |
| **4/28** | **Final Demonstration & Presentation Preparation** | Complete final demo, finalize documentation and video presentation, refine last-minute improvements. |
| **5/5** | **Final Presentation & Paper Submission** | Present findings to instructors, submit final project papers, complete peer evaluations. |

# Ethics and Safety

## Safety

1. This device is designed to improve water quality monitoring through automation, increasing efficiency and reducing human error. Since it will be relied upon for accurate water testing, it must be built to provide precise and repeatable results. Any inaccuracies in the system could lead to incorrect assessments of water quality, potentially causing harm to users.

2. The ACM Code of Ethics also emphasizes "minimizing negative consequences of computing, including threats to health, safety, personal security." Given that our device involves electronic components interacting with water, we will enforce strict safety measures, such as waterproofing and insulating all electrical elements. Additionally, we will conduct extensive testing to verify thermal and electrical safety and ensure that all components meet regulatory compliance standards.

## Ethics

Protecting user data and ensuring transparency is fundamental to our project. Since our system processes water quality data, we will implement security measures to prevent unauthorized access or data misuse. Our vision is to have no data transmitted out of the system onto a network. This will help protect their data and also can help prevent any malicious attacks. The ACM Code of Ethics states that honesty and trustworthiness are critical in product development, and we will uphold these principles by keeping users informed about how the system functions and ensuring full transparency. To promote accessibility, our system will be designed to accommodate users of varying technical expertise, including an intuitive user interface and clear documentation to ensure users can operate the system effectively.

## References

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[4] "Drinking Water Test Strips," Amazon, https://www.amazon.com/Water-Testing-Kits-Drinking-Hardness/dp/B0BG63JJ3T (accessed Feb. 12, 2025).
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