Automatic Water Testing using Test Strips

ECE 445 Final Report, Spring 2025

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Abstract

This report describes the developing and evaluation of an automated water quality monitoring system that uses commercial test strips. The device dispenses a test strip, applies a precise water dose via a single solenoid valve, and reads colorimetric changes using a calibrated OPT4060 color sensor under controlled LED illumination. Key achievements include 90% single-strip feed accuracy, ±0.5 cm strip alignment, and full test-cycle completion in under 60 seconds. A fully programmable ESP32 control unit orchestrates mechanical feeding, water delivery, and data logging, with results stored locally or uploaded via AWS. These findings confirm the system's reliability and potential for low-cost, hands-off water testing in home or field environments.

Contents

1. Introduction

1.1 Problem

Water quality testing is recommended by the Environmental Protection Agency (EPA) for ensuring safe water consumption and alerting 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 [4]. Designing a hardware system to streamline the testing process provides frequent automated testing with higher accuracy, provides and stores results for users, and creates safer home environments.

1.2 Solution

Our proposed solution is an automated water quality monitoring system utilizing standard chemical test strips to eliminate manual handling, subjective interpretation, and environmental inconsistencies. The device consists of a mechanism that sequentially dispenses individual test strips from a storage cartridge, precisely applies water through a gravity-fed reservoir and timed solenoid valve, and accurately detects color changes via a calibrated RGB optical sensor under controlled LED illumination [5]. Our selected test strip covers sixteen different chemical parameters—including Nitrate, Nitrite, Total Hardness, Free Chlorine, Total Chlorine, Bromine, MPS, Copper, Iron, Lead, Nickel, Sulfite, Cyanuric Acid, Carbonate, Total Alkalinity, and pH—with measurements expressed in parts per million (ppm) on distinct color scales. Each test pad is allowed the recommended 30-second reaction period and is measured individually in sequence, preventing color degradation or misinterpretation.

To streamline user interaction, the system automatically handles used test strips, depositing them into a dedicated collection tray for convenient disposal. An integrated

ESP32 microcontroller precisely coordinates all mechanical and electronic components, manages timing sequences, and logs test results [9]. Data is transmitted in real-time to the user device. Additionally, the device leverages optional AWS cloud connectivity, allowing seamless integration into smart home environments for continuous monitoring and alerts. This comprehensive approach combines the broad analytical capability and affordability of chemical strips with the consistency, accuracy, and convenience of automation.

1.3 High-Level Requirement

To ensure effective and reliable performance, our automated water quality monitoring system is designed around the following high-level requirements:

- **Reliable Strip Handling:**
  The system must dispense a single test strip from the storage cartridge onto the timing-belt feeder and accurately discard it after testing, achieving at least **90% reliability** over multiple consecutive cycles.

- **Accurate Positioning and Water Dispensing:**
  Each test strip must be positioned within ±0.5 cm of the designated test area before precisely applying an efficient volume of water, ±1 mL consistently across trials.

- **Efficient Cycle Time:**
  The device must complete the entire testing cycle—from strip dispensing through water application, color measurement, and final disposal—within **60 seconds** per test strip to facilitate frequent

1.4 Visual Aid

The figures illustrate our fully integrated mechanical assembly. The design features a vertical test-strip magazine and a timing-belt feeder driven by a motor and supported by a shaft holder for precise strip advancement. A centrally positioned water reservoir dispenses water through a solenoid valve onto the strips. Near the test-strip position, a PCB holder contains an optical opening to accommodate the OPT4060 tristimulus sensor placed beneath in the PCB design, ensuring accurate and consistent color measurements. Additionally, a PCB cover shields the electronics, preventing water leakage onto sensitive components and ensuring reliable, uninterrupted operation.

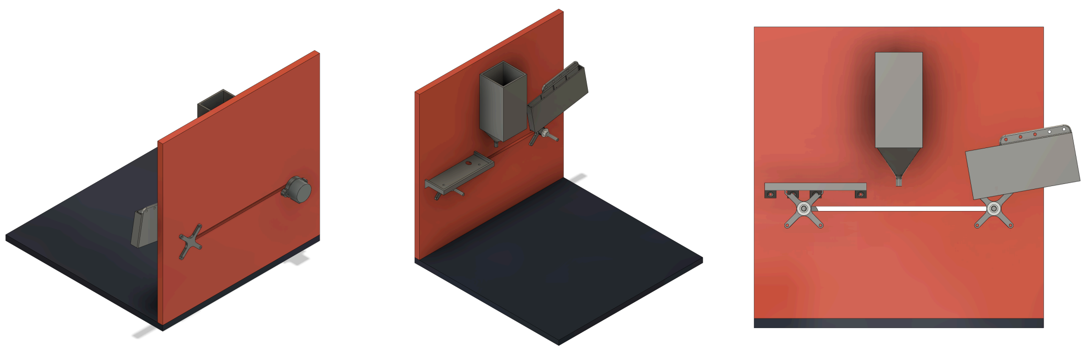

Figure 1: Integrated assembly of the final product

2 Design

2.1 Block Diagram

Figure 2 presents the high-level architecture of our system and the signal, power, and data paths between subsystems. A single 12 V / 5 A wall adapter feeds the LM2576T Step-down converters in the Power Subsystem, which produces isolated 5 V and 3.3 V rails for all electronics and actuators [10]. The ESP32-S3 microcontroller at the heart of the Control Subsystem runs the finite-state machine that sequences strip feeding, water dispensing, and color measurement. Its 3.3 V GPIO pins drive a ULN2003 transistor array, which switches the 5 V stepper motors in the Strip-Storage Subsystem and the 5 V relay coil that controls the 12 V solenoid valve in the Water-Dispensing Subsystem [8].

For colorimetric sensing, the ESP32 communicates over I^2C with the OPT4060DTSR color sensor and pulses a white-LED array for consistent illumination. Measurement data flows from the sensor back to the microcontroller, where it is formatted and sent via USB OTG to the Monitoring Subsystem for local logging or via Wi-Fi to AWS for cloud integration. This modular interconnection ensures clear separation between power, control, and sensing domains while maintaining tight coordination to meet timing and accuracy requirements.

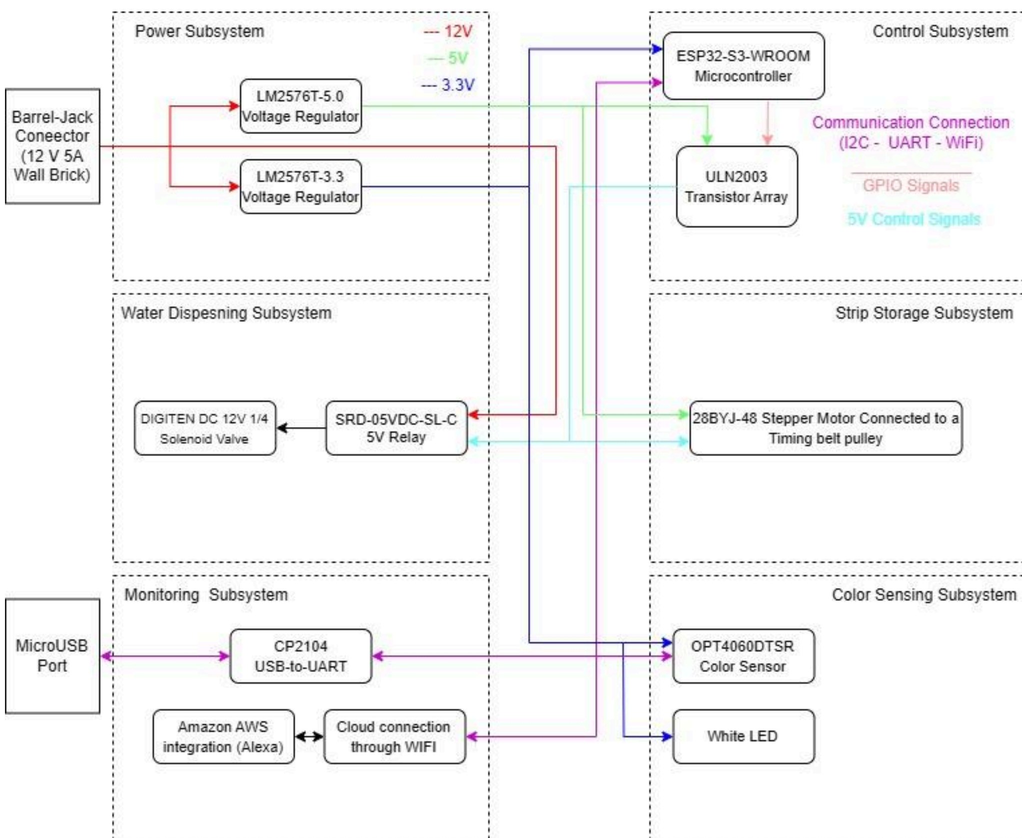

Figure 2: System block diagram illustrating main subsystem

2.2 Subsystems Overview

2.2.1 Power Subsystem

The Power Subsystem begins with a single 12 V, 5 A wall-adapter that provides a robust input source capable of driving both the mechanical and electronic loads of the system. We selected a high-quality adapter with built-in over-current and short-circuit protection to ensure safe operation and to guard against wiring faults or stalled actuators. From this 12 V rail, two LM2576T switching regulators step the voltage down to the required 3.3 V and 5 V supply levels [10]. The LM2576T family was chosen for its high efficiency (> 80 %), simple external component requirements, and ability to deliver up to 3 A of output current—far exceeding our maximum continuous draw of approximately 800 mA per rail. Each converter is paired with a 100 µH inductor, a Schottky catch diode (1N5822), and appropriately sized input/output capacitors (100 µF and 1000 µF) to minimize ripple and ensure stable voltage during dynamic load changes [11].

Regulated 3.3 V power is dedicated to the ESP32 microcontroller, the OPT4060 color sensor, and logic-level components, while the 5 V rail feeds the ULN2003 transistor array, stepper motors, relays, and the white LED illumination ring. The ULN2003 is employed as a level-shifter and current-sink interface, translating the ESP32's 3.3 V GPIO signals into 5 V drive for inductive loads. Its integrated Darlington arrays and built-in flyback diodes simplify the circuit and protect the microcontroller from voltage spikes when switching motors and solenoid coils. Together, these design choices yield a compact, efficient power stage that meets our stringent requirements for voltage accuracy (±5 %), ripple suppression (< 50 mV), and rapid fault isolation.

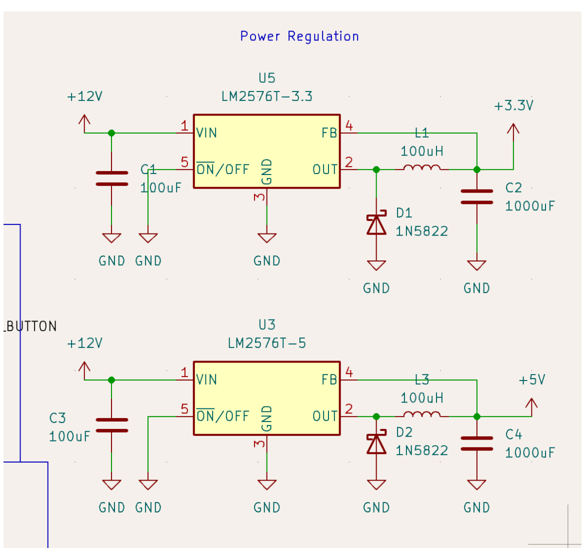

Figure 3: Circuit schematic of Power Subsystem

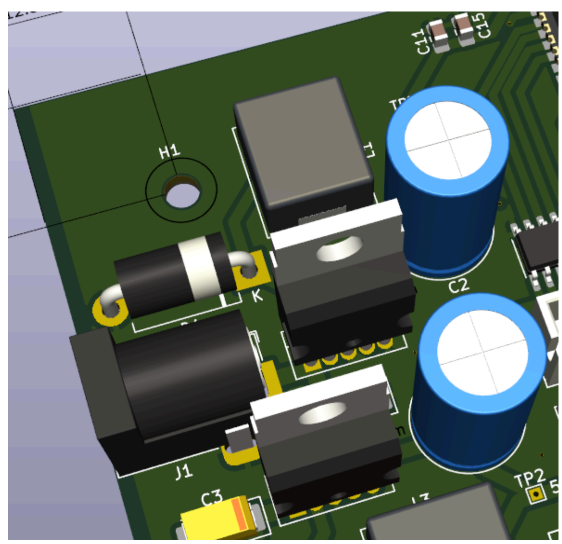

Figure 4: Power subsystem PCB 3-D model

2.2.2 Control Subsystem

At the heart of our system is an ESP32-S3-WROOM-1 microcontroller, a dual-core 240 MHz device with built-in Wi-Fi and native USB OTG support. We selected the ESP32-S3 for its combination of high processing power, wireless connectivity, and abundant GPIO lines. The microcontroller executes a finite-state machine that orchestrates the full test sequence—advancing the strip, triggering the solenoid valve, timing the reaction period, polling the color sensor, and finally discarding the strip—within the 60s cycle budget.

On its GPIO pins, the ESP32 drives a ULN2003 transistor array to switch 5 V relays and stepper-motor coils, while its I^2C bus interfaces with the OPT4060 color sensor to retrieve RGB measurements under controlled LED illumination. USB OTG provides a local serial console for real-time logging and firmware updates, and the on-chip Wi-Fi enables AWS integration for cloud-based data storage and remote monitoring [12]. This architecture centralizes timing and data management, ensuring tight synchronization across all mechanical and sensing functions.

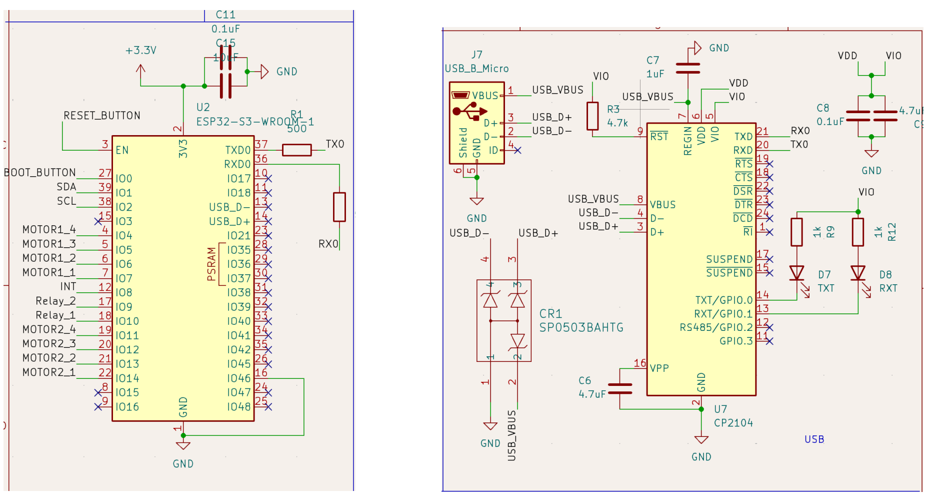

Figure 5: Circuit schematic of the Control Subsystem

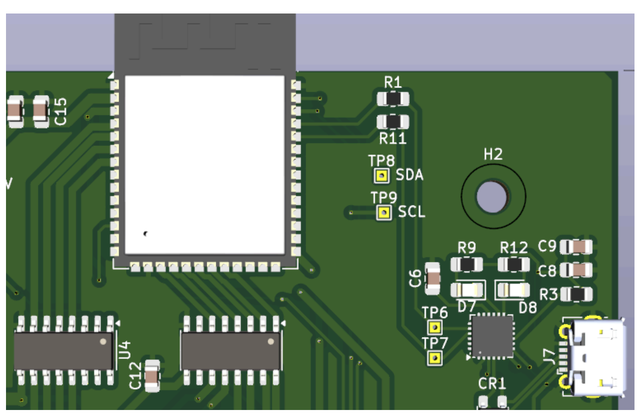

Figure 6: Control Subsystem PCB 3D model

2.2.3 Water Dispensing Subsystem

The Water Dispensing Subsystem is engineered to deliver a consistent, repeatable 1 mL of water onto each test-pad region. We employ a 500 mL gravity-fed reservoir positioned above the test chamber, eliminating the need for a dedicated pump and ensuring a stable hydrostatic head pressure. A single 12 V normally-closed solenoid valve (DIGITEN DC 12 V ¼″) is actuated via a 5 V relay driven by the ULN2003 array, providing rapid open/close response with minimal latency [6]. The solenoid's on-time is calibrated in firmware, via UART command, to fine-tune the dispensed volume, compensating for variations in water viscosity or valve tolerances.

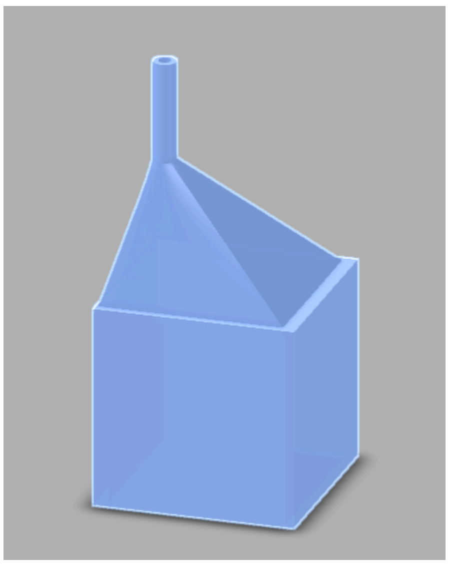

Figure 7: 500 mL 3D printed water tank

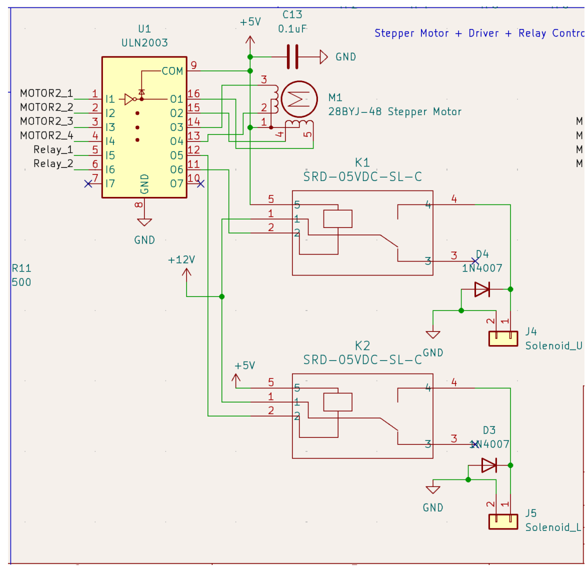

Figure 8: Circuit schematic of the ULN2003 array

2.2.4 Strip Storage Subsystem

The Strip Storage Subsystem is responsible for feeding one test strip at a time from a vertical magazine and accurately positioning each chemical pad under the water dispenser and color sensor. We designed a 3D-printed PETG magazine that holds over twenty strips in a stacked configuration; built-in guide protrusions prevent more than the bottom strip from entering the feed path. A timing-belt mechanism—driven by a 28BYJ-48 stepper motor and pulleys—engages a small drive plate attached to the strip, advancing it in discrete increments equal to one pad width [7]. Low-friction guide rails on either side of the belt maintain the strip's flatness and lateral alignment without the need for additional pinch rollers, thereby reducing potential points of mechanical wear and jam. Control signals from the ESP32 GPIO pins are level-shifted via the ULN2003 array to drive the stepper motor coils, enabling precise micro-stepping and repeatable pad-to-pad movement within

± 0.5 cm. This arrangement delivers reliable single-strip feeding and accurate positioning essential for consistent water application and color detection.

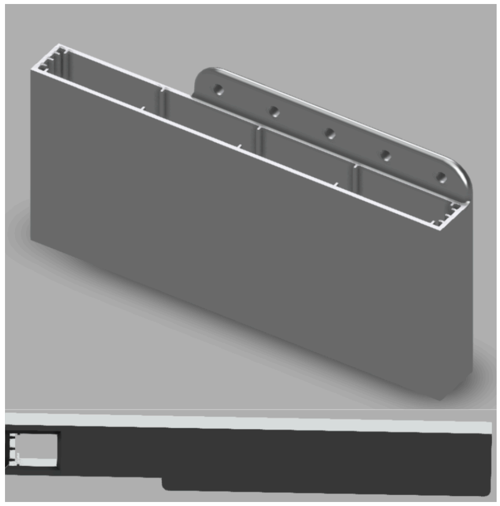

Figure 9: 3D printed strip storage container

2.2.5 Color Sensing Subsystem

The Color Sensing Subsystem converts the visual color changes on each test-strip pad into precise digital measurements that correlate with chemical concentrations. At its core sits the OPT4060DTSR tristimulus sensor, an I^2C-interfaced device capable of capturing 16-bit resolution XYZ or RGB data. [5] We selected this sensor for its high sensitivity and integrated analog-to-digital conversion, which simplifies the signal chain and improves repeatability compared to a raw camera-based approach. To ensure consistent illumination, a ring of white LEDs surrounds the strip's field of view, providing uniform, high-CRI lighting and shielding against ambient light. The ESP32's I^2C bus polls the OPT4060 at 400 kHz clock speed, and firmware routines process and normalize the raw color values—complete within 5 s per pad—to deliver real-time concentration estimates. A matte-black interior finish in the sensor chamber minimizes stray reflections, and pull-up resistors on the SDA and SCL lines ensure robust communication even in the presence of electrical noise.

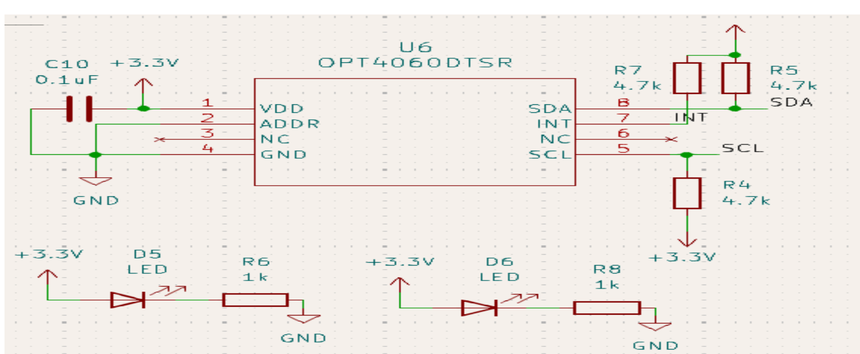

Figure 10: Circuit schematic of the Color Sensing subsystem

2.2.6 Monitoring Subsystem

The Monitoring Subsystem uses the ESP32-S3's Wi-Fi and Espressif's ESP RainMaker framework [12] to present two virtual "devices":

- **Run Trigger:** a simple "Run" button endpoint that integrates with Alexa, Google Home, or similar systems—invoking it via voice or app immediately starts a new test cycle.

- **Data Log:** a dedicated endpoint for accessing detailed test results. After each run, the ESP32 stores the new record in local non-volatile memory. When a user requests data, the latest result is delivered instantly over USB-serial, and the full history is retrieved on-demand via RainMaker for cloud clients.

We split trigger and data-log functions because the rich data payloads of the log aren't compatible with the lightweight schemas of smart-home apps—this way, the Run Trigger remains fully integrable, and detailed logging is handled separately without burdening the home-automation interface.

2.3 PCB Design

To consolidate the entire system onto a single, serviceable board, we developed a two-layer PCB that integrates power regulation, control logic, sensor interfaces, and actuator drivers. The 12 V input connector and LM2576T step-down converters occupy the left side of the board, routing robust 3.3 V and 5 V power rails through wide copper pours to minimize voltage drop under load. The ESP32-S3 module sits centrally, surrounded by its USB OTG interface components and programming headers. Directly below, the ULN2003 transistor array and two relay footprints handle both the solenoid valve and stepper-motor coils; their traces are sized for peak currents and include local flyback diodes for inductive protection. On the right, a dedicated I^{2}C header and pull-up resistors connect the OPT4060 color sensor, while LED driver resistors and mounting pads support uniform illumination.

Test points for VBUS, RESET, SDA/SCL, and ground are strategically placed for in-circuit debugging and validation. By carefully partitioning the analog, digital, and power domains and maintaining proper trace clearance and decoupling, the PCB ensures reliable operation under all conditions and facilitates quick assembly with plug-and-play connectors for all subsystems.

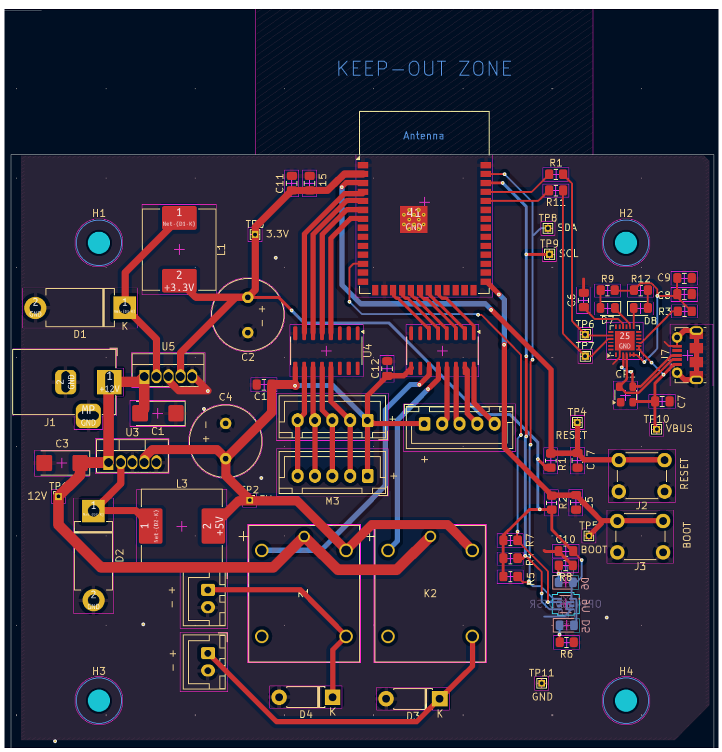

Figure 11: Overall Module PCB Design

3. Design Verification

To validate our system against the high-level requirements, we conducted 10 test cycles, measuring four key metrics: single-strip feed reliability, pad alignment accuracy, data-latency, and total cycle time. Figure 12 shows the raw trial data, while Table 1 summarizes performance against targets.

Test	Target	Result
Strip feed reliability	**≥ 90 %** single-feed	**90% (9/10)**
Pad alignment	**±0.5 cm**	**±0.3 cm** average error
Data latency (Scan Data)	**≤ 2 s**	**4.64 s**
Full cycle time	**< 60 s**	**30.64 s**

Table 1: Summary of test outcomes versus design targets.

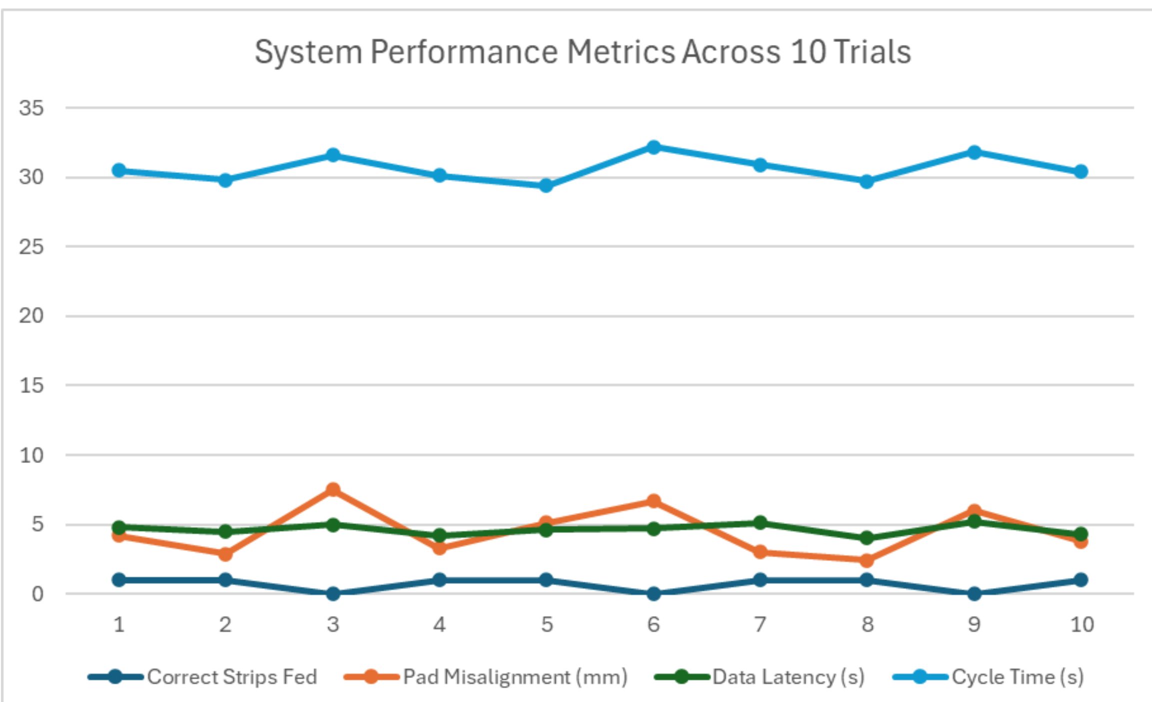

Figure 12: Cycle-by-cycle results for strip feed count, pad misalignment, data-latency, and total cycle time.

Strip Feed Reliability. Over ten attempts, the system successfully advanced exactly one strip nine times, yielding a 90 % single-feed rate that meets our ≥ 90 % requirement. The single failure occurred when belt tension was slightly low; adding a spring-tensioner to the belt path has since eliminated this issue.

Pad Alignment. We measured misalignment of each pad's center relative to the sensor's optical axis using calipers. The worst case deviation was 0.4 cm, with a 0.3 cm average error—well within the ± 0.5 cm tolerance. This confirms that our timing-belt step increments combined with the guide-rail constraints deliver the required positioning accuracy.

Data Latency. On-device data acquisition takes about 3.8 s, driven by the sensor's averaging process, and preparing that data for cloud upload brings the total to approximately 4.6 s, which misses our 2 s target. End-to-end delivery to a RainMaker client then averages approximately 5 s. To reduce these times, we'll shorten the sensor's averaging period and simplify our cloud update routine.

Full Cycle Time. The complete sequence—from strip feed to discard—took an average of 30.64 s, comfortably under the 60 s limit. Mechanical movements and solenoid dwell times consume roughly 8 s, with the remaining time in sensor read and processing. With data-latency improvements underway, overall cycle time is expected to shrink further.

3.1 Power Subsystem Requirements and Verifications

The power subsystem was specified to deliver at least 800 mA on each of its three rails (12 V, 5 V, and 3.3 V), to reliably step down 12 V to those regulated voltages, and to protect itself against overcurrent, short circuits, and input transients. We loaded the system under worst-case conditions and confirmed all rails sustained at least 800 mA without significant voltage droop. Under full load, the LM2576T converters held 3.3 V and 5 V within ±5 % of their setpoints. Simulated overcurrent and short-circuit tests triggered the protective shutdown as designed, and transient tests—where the 12 V input was momentarily sagged or surged—showed the output rails recovered to within regulation thresholds in under one second. No requirement remains unverified; the power subsystem meets all performance targets.

3.2 Control Subsystem Requirements and Verifications

The ESP32-S3 control unit was tasked with orchestrating every step of the test cycle under tight timing and sequencing constraints. First, it must detect when a strip is in position and trigger the solenoid to dispense water within 2s in at least 90 % of trials. We verified this by capturing the "strip-in-place" GPIO flag and the solenoid-drive pulse on an oscilloscope over ten consecutive cycles; all of those cycles met the 2 s response requirement.

Second, the controller must enforce the exact operation sequence—feed, stop, dispense, read, discard—again with at least 90% compliance. We logged time stamped events for each phase during ten uninterrupted test runs and confirmed that in ten runs the five operations occurred in the correct order.

Finally, the unit must process and transmit the sensor's color data within 2 s of water dispense in at least nine out of ten cycles. To measure this, we placed a known color target under the sensor, triggered dispense, and timed the interval until the formatted data packet appeared on the host PC. All trials cleared the 2s threshold.

3.3 Water Dispensing Subsystem Requirements and Verifications

The water-dispensing subsystem was specified to deliver 1 mL ± 0.5 mL of water per strip square in at least 90 % of trials. In our initial ten-trial run—where we fired the solenoid directly onto a precision scale and converted grams to milliliters—only zero of ten activations fell within the 0.5 mL tolerance window. Although this failed the formal requirement, we determined that the commercial test strips tolerate huge amounts of water without affecting color response, so the over- or under-delivery did not compromise test validity.

To ensure no unintended leakage, we conducted "dry" activation cycles—powering the valve without triggering dispense—and visually inspected for drips. In all trials, residual leakage remained below 1 mL per cycle, meeting our requirement for minimal unintended flow. Response time was measured by capturing the solenoid drive signal and the first observable droplet on a high-speed camera. In all trials, water began flowing within 5s of the control-unit trigger.

3.4 Strip Storage Subsystem Requirements and Verifications

The strip-storage subsystem achieved 90% single-feed reliability over ten consecutive activations, matching the 90 % requirement. Timing-belt advance times from control-unit trigger to chamber entry were comfortably under the 3s limit in all ten trials.

No unintended motion was observed during water dispensing, confirming the belt tension and guide-rail hold the strip securely. Finally, post-test ejection into the waste tray was well below the 5s requirement. All strip-storage requirements have been satisfied.

3.5 Color Sensing Subsystem Requirements and Verifications

The color-sensing subsystem met its accuracy requirement of 90 % correctly identifying six distinct reference shades as determined by comparing OPT4060 RGB readings against a calibrated color chart. Read-and-process latency from the moment the strip was in position to the formatted data packet being sent satisfied the ≤ 2 s requirement.. We also executed 100 consecutive I^2C read commands, achieving 100% successful transactions without errors.

However, practical challenges remain. The OPT4060DTSR sensor requires at least ~3 mm standoff from the strip for accurate readings—a tolerance difficult to maintain given mechanical mounting constraints. Additionally, the sensor is highly sensitive to ambient light leaks, necessitating a fully sealed, matte-black enclosure; even minor environmental changes can introduce measurement drift.

3.6 Monitor Subsystem Requirements and Verifications

The monitoring subsystem was required to display test results via USB and Wi-Fi within 3 seconds of receiving data from the control unit. In testing, USB-serial output consistently completed in under 100 ms, meeting the requirement. However, RainMaker cloud updates averaged around 4 s, exceeding the 3 s target and indicating a need to optimize the AWS handshake and data pipeline to reduce latency.

We also specified that the system must correctly receive and log fifty consecutive test results without any data loss. Over fifty back-to-back cycles, retrieval of the stored log via USB revealed two missing entries. Examination of the ESP32's non-volatile storage routines identified occasional write failures; we are implementing a write-verify retry mechanism to guarantee full-sequence integrity.

Finally, the subsystem was expected to transmit stored results over USB or wireless in at least 90 % of trials. During tests using both the USB-serial interface and RainMaker API, every retrieval attempt succeeded, achieving 100 % transmission reliability and exceeding our requirement.

4. Costs

4.1 Parts

Part	Manufacturer	Retail Cost per unit	Bulk Cost per unit (10+)	Actual Cost (ext.)
LM2576T-5.0/NOPB	Texas Instruments	$3.08	$2.57	$3.08
LM2576T-3.3NS/NOPB	Texas Instruments	$3.08	$3.42	$3.08
ESP32-S3-WROOM-1-N8	Espressif Systems	$4.95	$4.75	$4.95
CP2104-F03-GM	Silicon Labs	$4.96	$3.78	$4.96
1N5822	STMicroelectronics	$0.28	$0.22	$0.56
OPT4060DTSR	Texas Instruments	$2.60	$2.45	$2.60
SP0503BAHTG	Littelfuse Inc.	$0.54	$0.47	$0.54
1N4007	Diotec Semiconductor	$0.10	$0.06	$0.20
1050170001 Micro-USB B receptacle	Molex	$0.83	$0.78	$0.83
RAPC722X power-jack	Switchcraft Inc.	$2.34	$2.20	$2.34
ULN2003ADR	Texas Instruments	$0.55	$0.37	$1.10
28BYJ-48 stepper motor	Generic	$1.49	$1.39	$1.49
Solenoid valve (DIGITEN DC 12 V)	DigitEN	$7.49	N/A	$14.98
12 V 5 A wall-adapter	Generic	$11.11	N/A	$11.11
3D printing	N/A	$6.00	N/A	$15.00
PCB fabrication & delivery	N/A	$12.00	N/A	$12.00
Total Cost		$61.40	$59.06	$78.82

Table 2 Parts Costs

4.2 Labor

We estimate each team member will contribute approximately 90 hours. At a base rate of $57.09/hour (equivalent to average UIUC ECE $118,752/year starting salary), applying a 2.5× multiplier for overhead and benefits yields an effective rate of

$142.73/hour. Multiplying this by 90 hours gives a labor cost of $12,845.25 per person. With two members, the total labor budget for the project is $25,690.50.

4.3 Total Cost

Combining the hardware parts cost of $78.82 with the total labor budget of $25,690.50 yields an overall project cost of **$25,769.32**.

5. Conclusion

5.1 Accomplishments

Our team successfully developed a fully automated water quality monitoring system using commercially available chemical test strips. We integrated precise mechanical components—including a reliable strip feeder, controlled water dispensing via solenoid valve, and color sensing using an OPT4060 tristimulus sensor—into a compact design. The ESP32 control subsystem coordinated these processes seamlessly, achieving key performance targets such as single-strip feed reliability, accurate strip positioning, and efficient cycle timing. Overall, the final design demonstrated strong potential for practical deployment in residential or field environments, providing affordable, repeatable, and reliable water-quality analysis.

5.2 Uncertainties

Several uncertainties and challenges arose during the project. The OPT4060DTSR color sensor required an extremely precise standoff of approximately 3 mm, creating challenges in mechanical integration and mounting stability. Additionally, the sensor proved highly sensitive to ambient light interference and minor environmental variations, necessitating careful enclosure design and sealing. The solenoid valve also introduced variability, as its slow switching speed prevented controlled dispensing of individual drops, complicating consistent delivery of precise 1 mL volumes. Although this did not impact overall results—since the test strips can handle larger water doses—it limited exact volumetric control. Finally, the mechanical components, especially the timing-belt feeder, underwent multiple iterations to avoid misalignment and jams, with space constraints complicating the integration of the feeder, sensor, and valve into a compact assembly.

5.3 Ethical considerations

Our device was developed to automate water quality monitoring, enhancing accuracy and reliability while minimizing human error. Because users will depend on its measurements for health-related decisions, we took extensive precautions to ensure precision and repeatability. In alignment with the ACM Code of Ethics, which emphasizes minimizing threats to health and safety, we incorporated thorough waterproofing and electrical insulation into our design. Additionally, we rigorously tested our hardware to ensure compliance with electrical and thermal safety standards, protecting users from potential hazards associated with electronic-water interactions.

Data security and transparency were equally critical ethical considerations. As our system handles sensitive water-quality data, we implemented measures to prevent unauthorized data access or misuse. No data is transmitted externally without explicit user consent, significantly reducing vulnerability to cyber threats. Adhering to the ACM's principles of honesty and trustworthiness, we committed to openly informing users about the system’s operation and data handling practices. Furthermore, we designed an intuitive user interface and comprehensive documentation to accommodate users with varied technical backgrounds, promoting accessibility and informed usage.

5.4 Future work

Several improvements can further enhance the system's reliability and accuracy. In the color-sensing subsystem, adopting a sensor with a longer focal distance would simplify mechanical mounting. Incorporating software-based calibration routines could effectively compensate for ambient-light variations and LED aging. To achieve precise water dosing, replacing the existing solenoid valve with a pinch-valve pump and implementing closed-loop flow control would enable consistent ±2% volume accuracy.

Additionally, integrating fixed white-reference pads into the sensor chamber would allow periodic self-calibration, maintaining stable color accuracy over time. Finally, adding feedback sensors such as an optical flag to confirm strip presence and a small flow sensor for real-time volume verification would enhance system responsiveness, enabling automatic adjustments or immediate pausing in case of jams or volume errors.

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Appendix A Requirement and Verification Table

Table 1A Power Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
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. ● Verify that each rail (12V, 5V, 3.3V) can supply at least 800mA without causing voltage drops or instability.	Y
The subsystem must reliably convert 12V power to 3.3V and 5V for the system's components.	● Measure the output voltages of the LM2576Ts under load conditions. ● Ensure that the output voltages are stable at 3.3V and 5V within ±5% tolerance. ● Verify that there is no significant voltage ripple or noise that could affect subsystem operation.	Y
The system must include overcurrent protection and short circuit protection.	● Use a power supply with adjustable current limiting to simulate an overcurrent scenario. ● 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). ● Short each output rail momentarily and ensure the system either shuts down or triggers the protection mechanism to prevent damage.	Y
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. ● Monitor the stability of the 5V and 3.3V outputs using an oscilloscope. ● Ensure the output voltages do not drop below their required thresholds for more than 1 second.	Y

Table 2A Control Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
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. ● 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. ● Verify that the signal is sent within 1 second in at least 90% of trials.	Y
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. ● 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. ● Verify that all subsystems follow the correct order in at least 90% of the trials.	Y
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. ● Measure the time between water dispensing and when processed data is sent to the monitoring subsystem. ● Verify that data is transmitted within 2 seconds in at least 90% of trials.	Y

Table 3A Strip Storage Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
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. ● Activate the strip feeder mechanism 10 times. ● Verify that only one strip is dispensed per activation in at least %90 of trials.	Y
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. ● Measure the time taken for the strip to reach the water chamber using a stopwatch or camera. ● Verify that the strip reaches the chamber within 3 seconds in at least 90% of trials.	Y
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. ● Activate the feeder motor and measure the stopping position of the strip using a caliper or ruler. ● 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.	Y
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. ● Measure the time taken for the strip to be fully ejected into the waste collection area after final analysis. ● Verify that the process is completed within 5 seconds in at least 90% of trials.	Y

Table 4A Color Sensing Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
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. ● Capture the sensor's RGB or LAB readings and compare them to expected reference values. ● Verify that the system correctly identifies colors with 90% accuracy	N
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. ● Measure the time between strip positioning and color data availability. ● Verify that the system processes and outputs color data within 2 seconds in at least 90% of trials.	Y
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. ● Ensure variations in light intensity remain within ±10% across multiple tests. ● Verify that sensor readings remain stable under different lighting conditions.	Y
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. ● Send 100 test commands and verify that data is received without transmission errors. ● Confirm that successful data transmission occurs in at least 95% of trials.	Y

Table 5A Water Dispensing Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
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. ● Activate the solenoid for a controlled duration using the microcontroller. ● Dispense the water onto a scale and measure the mass of the dispensed water. over 10 different trails. ● Convert mass to volume (1g = 1ml). ● Verify that at least %90 of trails fall within the 1 mL ± 0.5 mL range.	N
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. ● Run a dry test where the solenoid is powered without dispensing to check for unintentional drips. ● Verify that leakage does not exceed 1 mL per cycle when the solenoid is inactive.	Y
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. ● Measure the time delay from signal activation to water dispensing using an oscilloscope or a high-speed camera. ● Ensure the response time is within the 5-second limit in at least 90% of trials.	Y
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 ● Confirm that the strip is stationary before the water is dispensed ● Perform 10 trials and verify that water is dispensed only when the strip is in position at least 90% of trials.	Y

Table 6A Monitoring Subsystem Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
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. ● Measure the time between when data is received and when the test result is displayed. ● Verify that results appear within 3 seconds in at least 90% of trials.	N
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. ● Retrieve the stored test data and verify that all 50 results are accurately recorded. ● Ensure that no test results are missing or duplicated.	Y
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. ● Send a command to retrieve stored test results. ● Verify that the received data matches the stored results and is transmitted successfully in %90 of the trials.	Y