ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

AdheraScent: Final Report for ECE 445

Team #58

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1 Introduction

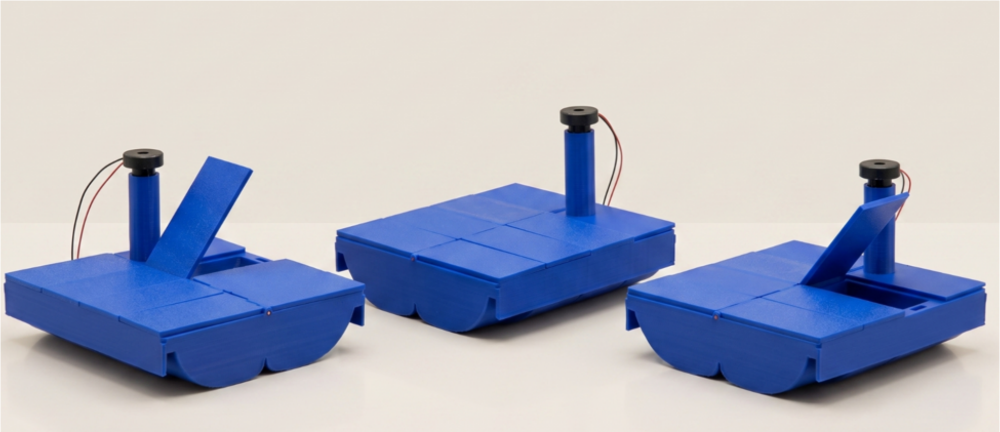


Figure 1: Product Image

1.1 Purpose

Consistent medication adherence is a fundamental pillar of healthcare, yet it remains a significant challenge, particularly for the aging population. As individuals age, cognitive functions, vision, and hearing often diminish, making it difficult to manage complex daily regimens. Traditional auditory or visual notifications are frequently lost in the pervasive ”noise” of modern digital environments, where users are saturated with constant alerts. Furthermore, many existing smart medical devices suffer from a high barrier to entry due to intimidating user interfaces and complex setup procedures, such as manual time setting. These design hurdles often lead to the abandonment of the device rather than improved health outcomes.

To address these challenges, we developed **AdheraScent**, an automated smart pill dispenser that utilizes scent as the primary notification mechanism. By leveraging the olfactory sense—which is less susceptible to the ”notification fatigue” associated with sight and sound—AdheraScent provides a distinct, gentle, yet persistent reminder that a dose is due. The system minimizes user frustration by automating technical tasks like time synchronization and ensures adherence through a closed-loop feedback system that only ceases notification once the medication is physically accessed.

1.2 Functionality

The AdheraScent system provides four core high-level functionalities that directly support its purpose of improving patient health:

- **Olfactory Notification:** The system triggers a modified ultrasonic aroma diffuser to release a perceptible scent within 5 seconds of a scheduled dose. This bypasses traditional sensory fatigue by using a unique stimulus to alert the user.

- **Verifiable Adherence:** Unlike standard alarms that can be dismissed with a button, the scent persists until the user physically opens the correct medication compartment. This ensures the user has engaged with their medication before the "alarm" stops.
- **Automated Time Sync:** The device captures a local timestamp via an integrated web server and keeps it in an external Real Time Clock (RTC). This removes the technical burden of manual clock setting, making the device accessible to users with low technological literacy.
- **Localized Scheduling Interface:** Users or caregivers can manage schedules via a smartphone connected to the device's internal Wi-Fi network. This provides a simple, intuitive interface while keeping all data local to protect user privacy.

1.3 Subsystem Overview

This section details the top-level architecture of the project, which is partitioned into four primary functional subsystems. These systems work together to manage power, process logic, provide user interaction, and interface with the physical environment.

1.3.1 Top-Level System Diagram

The following diagram (Figure 2) illustrates the modular design and the flow of power and data throughout the system.

1.3.2 Project Subsystems

1. Power Subsystem The Power Subsystem is the energy hub of the device, supporting both stationary and portable operation.

- **Input Sources:** Accepts 5V via USB-C or 3.7V from a Li-ion Battery.
- **Management:** A Charger IC handles battery replenishment, while a Protection IC ensures safe discharge cycles.
- **Distribution:** An OR-ing circuit manages the power path, feeding a Voltage Regulator that provides stabilized **3.3V** (logic) and **5V** (actuation) rails.

2. Control Subsystem The Control Subsystem serves as the "brain" of the project, managing timing and execution logic.

- **Microcontroller:** An ESP32-S3-WROOM module handles high-level logic, Analog-to-Digital Converter (ADC) sampling, and signal generation.
- **Timing:** A Real-Time Clock (RTC) provides accurate time-stamping, supported by an independent CR1220 backup battery.
- **Debug Interface:** A dedicated UART header is provided for serial debugging and firmware updates.

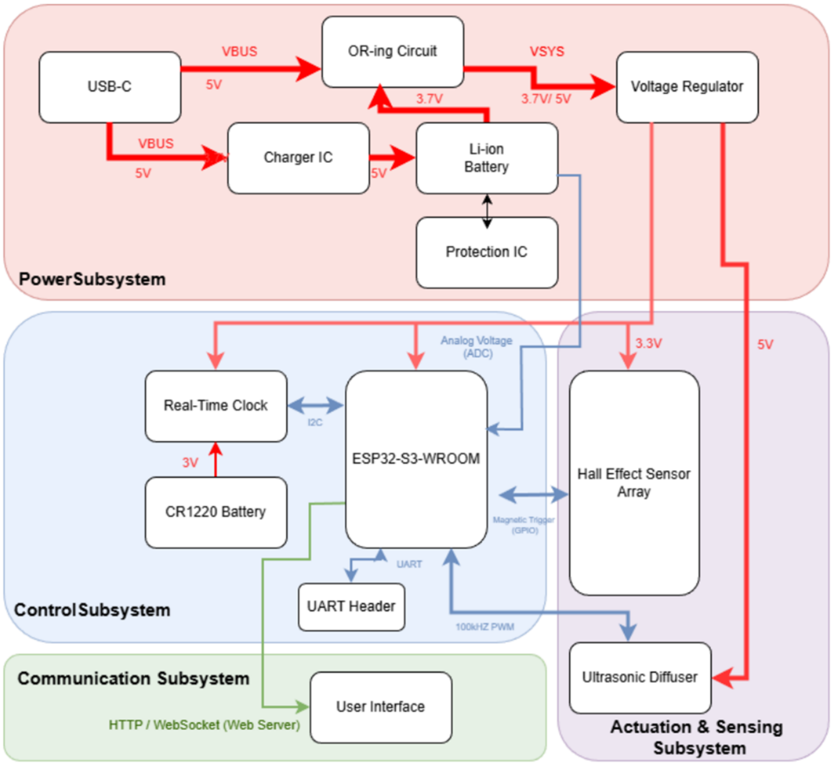


Figure 2: System Architecture Block Diagram highlighting power paths (red) and data signals (blue/green).

3. Communication Subsystem This subsystem facilitates wireless interaction between the hardware and the user.

- **User Interface:** The ESP32 hosts a Web Server that serves a User Interface (UI) via **HTTP** and **WebSockets**, allowing for real-time monitoring and control from any browser.

4. Actuation & Sensing Subsystem This block enables physical interaction through sensor inputs and mechanical outputs.

- **Sensing:** A Hall Effect Sensor Array detects external magnetic triggers, signaling the MCU via GPIO.
- **Actuation:** An Ultrasonic Diffuser is driven by a precise **108.5kHz PWM** signal from the MCU to atomize liquid.

2 Design

The AdheraScent device is a modular system designed to provide reliable medication reminders through a non-intrusive olfactory mechanism. The architecture is centered around an **ESP32-S3-WROOM-1** microcontroller, which manages power, logic execution, scent actuation, and compliance sensing through four distinct subsystems.

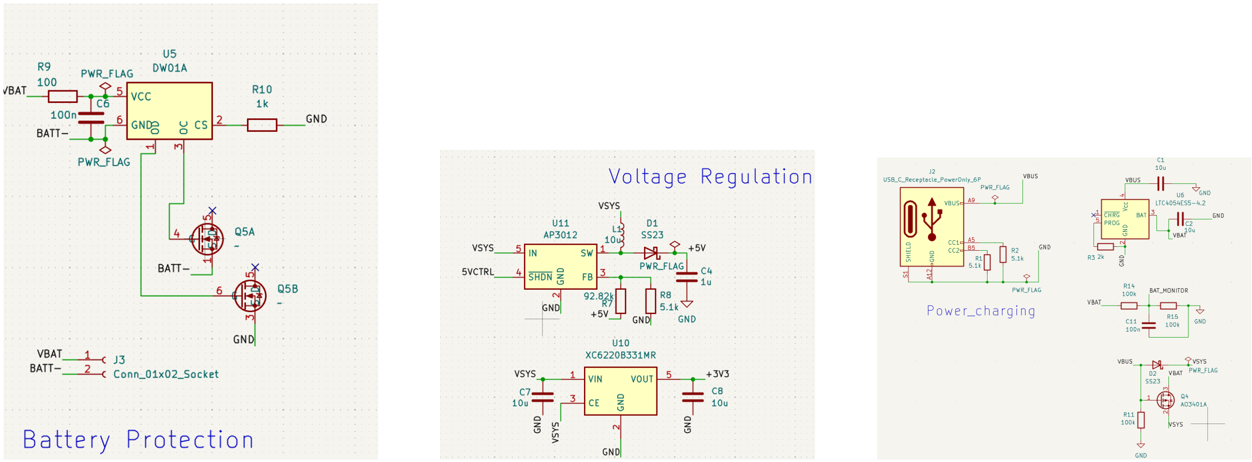
2.1 Power Subsystem

2.1.1 Description & Justification

The Power Subsystem provides stable, regulated rails to support simultaneous high-current demands: a 3.3V logic rail for the ESP32 and sensing array, and a 5.0V actuator rail for the ultrasonic atomizer.

- **Power Path Management (OR-ing):** Uses a Schottky diode and a P-Channel MOSFET to automatically switch between USB-C power (V_{BUS}) and battery power (V_{BAT}).
- **Battery Management:** Utilizes an **LTC4054** linear charger for the Li-ion battery and a **DW01A** protection IC with dual N-Channel MOSFETs to prevent over-charge, over-discharge (cutoff at 2.5V), and over-current conditions.
- **Voltage Regulation:** An **XC6220** LDO provides a clean 3.3V rail (up to 300mA) for logic stability, while an **AP3012** Step-Up converter generates the 5.0V rail (up to 800mA) for the atomizer.

2.1.2 Schematics



(a) Circuitry A (b) Circuitry B (c) Circuitry C

Figure 3: Power Subsystem Circuitry Overview

2.2 Control Subsystem

2.2.1 Description & Justification

The Control Subsystem serves as the central processing unit, managing timing schedules and wireless connectivity.

- **Timing Integrity:** The system utilizes an internal clock synchronized via NTP over Wi-Fi, complemented by an external hardware I2C RTC (**DS3231**) with a CR1220 backup battery to maintain schedules during power outages.
- **I/O Processing:** The MCU monitors up to 7 Hall Effect sensors via GPIO interrupts and manages actuation via the **DIFF_TRIG** signal.
- **Battery Monitoring:** An ADC pin monitors the **BAT_MONITOR** voltage divider to track the state-of-charge accurately within $\pm 0.1V$.

2.2.2 Schematics

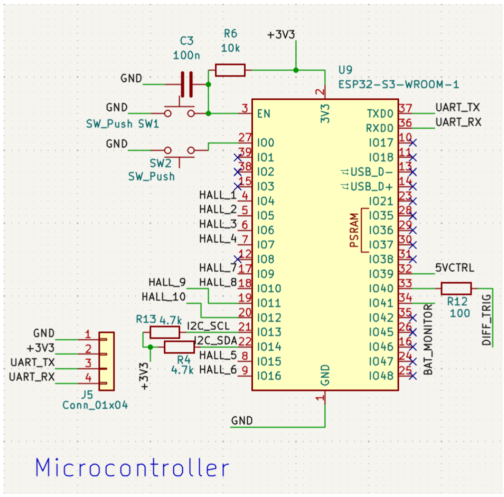


Figure 4: Control Subsystem and Microcontroller Interface A

2.3 Actuation & Sensing Subsystem

2.3.1 Description & Justification

This subsystem executes the physical notification and tracks adherence through a closed-loop feedback mechanism.

- **Mist Generation:** An ultrasonic atomizer is driven by an **AO3422** N-Channel MOSFET. A 10 $k\Omega$ pull-down resistor ensures the actuator remains off during MCU boot/reset states.
- **Signal Integrity:** An LC filter (100 μH inductor with 10 μF/100 nF capacitors) suppresses power supply ripples ($< 150mV$) caused by the atomizer's high-frequency draw.

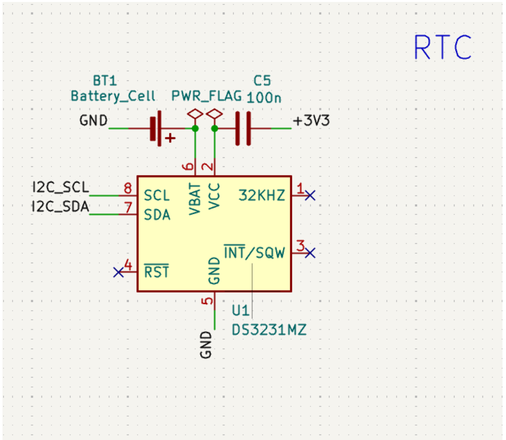
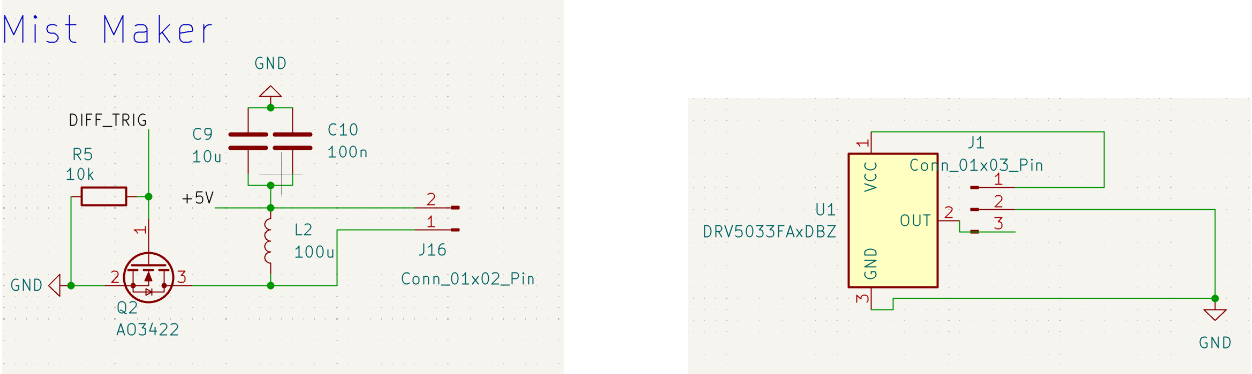


Figure 5: Control Subsystem and Microcontroller Interface B

- **Adherence Tracking:** A Hall Effect sensor array detects magnets embedded in the pillbox lids. The system ensures 100% detection accuracy to verify that a compartment has been physically opened.

2.3.2 Schematics



(a) Actuation and Sensing Circuitry A

(b) Actuation and Sensing Circuitry B

Figure 6: Overview of Actuation and Sensing Circuitry

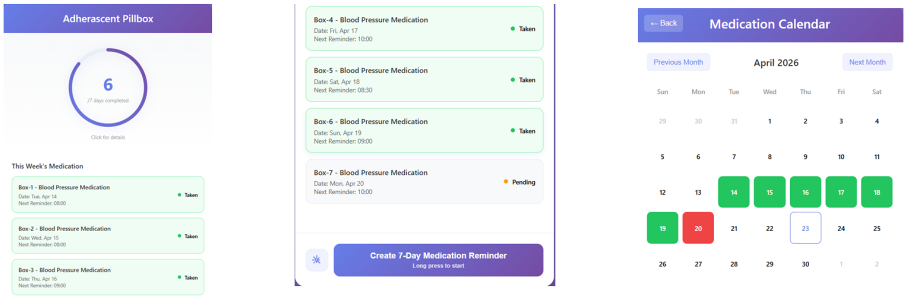
2.4 Communication Subsystem

2.4.1 Description & Justification

The Communication Subsystem provides a localized, user-friendly interface to minimize technological friction for the elderly.

- **SoftAP Mode:** The ESP32 hosts a local Wi-Fi network, allowing users to connect via smartphone to a localized web server (HTTP/WebSocket) without requiring home internet access.

- **Data Persistence:** User-defined medication schedules are parsed and saved to the ESP32's Non-Volatile Storage (NVS) to ensure alarm configurations survive power cycles.
- **Security:** Localized hosting eliminates cloud-based data breach risks, keeping patient scheduling data strictly on the device.



This Week's Medication

Box-1 - Blood Pressure Medication
Date: Tue, Apr 14
Next Reminder: 08:00
● Taken

Box-2 - Blood Pressure Medication
Date: Wed, Apr 15
Next Reminder: 08:00
● Taken

Box-3 - Blood Pressure Medication
Date: Thu, Apr 16
Next Reminder: 09:00
● Taken

Box-4 - Blood Pressure Medication
Date: Fri, Apr 17
Next Reminder: 10:00
● Taken

Box-5 - Blood Pressure Medication
Date: Sat, Apr 18
Next Reminder: 08:30
● Taken

Box-6 - Blood Pressure Medication
Date: Sun, Apr 19
Next Reminder: 09:00
● Taken

Box-7 - Blood Pressure Medication
Date: Mon, Apr 20
Next Reminder: 10:00
● Pending

April 2026

Sun	Mon	Tue	Wed	Thu	Fri	Sat
29	30	31	1	2	3	4
5	6	7	8	9	10	11
12	13	🟩 14	🟩 15	🟩 16	🟩 17	🟩 18
🟩 19	🟥 20	21	22	23	24	25
26	27	28	29	30	1	2

Figure 7: Communication Subsystem User Interface

2.5 Equations & Tolerance Analysis

The critical technical challenge is generating the high-voltage transient ($V_{pk} \geq 30V$) required to drive the piezoelectric atomizer from a 5V DC rail using a single-inductor boost topology.

Inductive Energy Transfer: During the MOSFET ON-time (t_{on}), the inductor current ramps linearly to a peak (I_{pk}):

$$I_{pk} = \frac{V_{in}}{L} \cdot \left(\frac{D_{nom}}{f_s} \right) = \frac{5V}{100\mu H} \cdot 3.63\mu s = 0.1815A \tag{1}$$

Resonant Voltage Generation: Upon MOSFET turn-off, the stored inductive energy (E_L) transfers to the atomizer's parasitic capacitance ($C_p \approx 3nF$):

$$V_{pk} = I_{pk}\sqrt{\frac{L}{C_p}} = 0.1815A \cdot \sqrt{\frac{100\mu H}{3nF}} \approx 33.1V \tag{2}$$

Worst-Case Margin Analysis: A software fault causing a duty cycle drift to 50% ($D_{max} = 0.5$) would increase I_{pk} to 0.227 A, resulting in:

$$V_{pk(max)} = 0.227A \cdot 182.57 \approx 41.4V \tag{3}$$

The **AO3422** MOSFET features a 55V breakdown rating, providing a 13.6V safety margin (55V - 41.4V), ensuring electronic reliability without needing aggressive TVS clamping that would reduce atomization efficiency.

2.6 Design Alternatives & Justification

- **Sensor Selection (Switch-type Hall Effect):** We opted for a switch-type Hall effect sensor instead of mechanical microswitches or linear Hall sensors. Unlike microswitches, Hall sensors are solid-state and frictionless, eliminating mechanical wear and extending the device's lifespan. Compared to linear Hall sensors, the switch-type variant provides a clear binary output via an internal Schmitt trigger; this simplifies the firmware logic and reduces MCU overhead by eliminating the need for continuous ADC sampling and threshold calibration.
- **Thermal vs. Ultrasonic:** Heat-based scent dispersal was rejected due to fire hazards and power inefficiency. Ultrasonic atomization operates at low temperatures, ensuring user safety during refilling and daily use.
- **Connectivity:** We chose a localized web server over a dedicated mobile app. This removes the need for account creation or app store updates, making the device more accessible to non-technical users and caregivers.

3 Cost and Schedule

3.1 Cost Analysis

The cost of the AdheraScent project is divided into two primary categories: component costs (Bill of Materials) and labor. The labor is calculated based on the standard rate for an entry-level engineer graduating from the University of Illinois at Urbana-Champaign; a comprehensive breakdown of these component costs is provided in the Detailed BOM in Appendix A.

Cost Category	**Description**	**Unit Price (USD)**	**Quantity**	**Total (USD)**
Hardware (BOM)	Electronic Components	$27.73	5 units	$277.30
Hardware (BOM)	PCB (99x80mm, 2-layer)	$5.00	5 units	$25.00
Labor (NRE)	UIUC ECE Engineer A	$60.00/hr	130 hrs	$7800.00
Labor (NRE)	UIUC ECE Engineer B	$60.00/hr	130 hrs	$7800.00
			Estimated Total Project Cost:	**$1,5763.65**

Table 1: Project Cost Analysis Simulation (13-Week Part-time)

3.2 Schedule

The project followed a strict 13-week development cycle, balancing mechanical fabrication with firmware and hardware integration; a comprehensive breakdown of these milestones is available in the Detailed Schedule in Appendix B.

4 Requirements & Verification

4.1 Power Subsystem

4.1.1 Requirements & Verifications

Table 2: Power Subsystem Requirements and Verifications

Requirement	**Verification Procedure**	**Success Criterion**
1. Battery Charging Current: The LTC4054 charger IC must provide a constant charging current of 500 mA ± 50 mA to the battery when powered via USB-C.	1. Connect a partially discharged Li-ion battery (approx. 3.5V) to the battery terminal. 2. Connect a digital multimeter (DMM) in series to measure current. 3. Plug a 5V source into the USB-C receptacle.	The DMM measures a continuous current between 450 mA and 550 mA flowing into the battery.
2. Logic Voltage Regulation: The XC6220 LDO must output a stable logic voltage of 3.3V ± 0.15V under a continuous load of up to 300 mA.	1. Power VSYS using a bench power supply set to 3.5V. 2. Connect a 3.3V-compatible electronic load set to 300 mA to the +3V3 output. 3. Measure the +3V3 rail with a DMM.	The DMM reads a voltage strictly between 3.15V and 3.45V.
3. Actuator Power Control: The Boost Converter must maintain an output voltage of 5.0V ± 0.2V only when the 5VCTRL signal is logic HIGH (> 1.5V).	1. Apply 3.7V to VSYS. 2. Apply 3.3V (Logic HIGH) to the 5VCTRL pin and measure the +5V output. 3. Apply 0V (Logic LOW) to the 5VCTRL pin and measure the +5V output.	The rail measures 4.8V to 5.2V during Step 2. The rail is disabled during Step 3.
4. Over-Discharge Protection: The Battery Management System (BMS) must cut off power output if the battery voltage drops below 2.5V.	1. Connect a variable bench power supply to the battery input terminals. 2. Apply a 100 mA load to the VSYS rail. 3. Gradually decrease the power supply voltage from 3.7V down to 2.0V while monitoring the load current.	The load current drops to 0 mA exactly when the bench power supply voltage reaches between 2.4V and 2.6V.

4.1.2 Quantitative Results

This section details the experimental results obtained from the verification procedures for the power management and control systems. All hardware requirements were successfully met, with measured values falling within the specified tolerance ranges.

4.1.3 Measurement Summary

The experimental data for each requirement is summarized in Table 3. Specific observations for each test case follow.

- **Battery Charging Current:** With a partially discharged Li-ion battery (3.5V) connected and a 5V USB-C source applied, the LTC4054 charger IC provided a steady charging current. The Digital Multimeter (DMM) recorded a continuous current of **492 mA**, which is well within the target range of 500 mA ± 50 mA.
- **Logic Voltage Regulation:** The XC6220 LDO was tested under a continuous 300 mA electronic load. The output voltage remained stable at **3.28 V**. This result satisfies the requirement of 3.3 V ± 0.15 V (3.15V – 3.45V).
- **Actuator Power Control:** The Boost Converter's performance was verified by toggling the 5VCTRL signal.
  - When 5VCTRL was HIGH (3.3V), the output voltage measured **5.04 V**.
  - When 5VCTRL was LOW (0V), the output voltage dropped to **0 V**, confirming the rail was successfully disabled.

  Both states align with the success criteria of 5.0 V ± 0.2 V and complete shutdown.
- **Over-Discharge Protection:** During the voltage ramp-down test, the BMS successfully cut off the power output when the simulated battery voltage reached **2.48 V**. The load current dropped from 100 mA to 0 mA instantly, satisfying the requirement for a cutoff between 2.4V and 2.6V.

Table 3: Summary of Quantitative Results vs. Requirements

Requirement	**Target Range**	**Measured Value**	**Status**
Charging Current	$450 - 550$ mA	492 mA	PASS
Logic Voltage (+3V3)	$3.15 - 3.45$ V	3.28 V	PASS
Boost Output (Active)	$4.8 - 5.2$ V	5.04 V	PASS
BMS Cutoff Voltage	$2.4 - 2.6$ V	2.48 V	PASS

4.2 Control Subsystem

4.2.1 Requirements & Verifications

Table 4: Control Subsystem Requirements and Verifications

Requirement	Verification Procedure	Success Criterion
1. Sensor Input Latency: The microcontroller must register a state change (Logic HIGH to LOW) on any HALL_X pin and execute the corresponding interrupt/callback within 200 ms.	1. Power the system and connect an oscilloscope to the HALL_1 input and a designated debug output pin. 2. Configure the firmware to toggle the debug pin immediately upon detecting a falling edge on HALL_1. 3. Manually pull HALL_1 to GND and measure the time delta between the falling edge of HALL_1 and the rising edge of the debug pin.	The measured time delta on the oscilloscope is $\leq$ 200 ms for 10 consecutive trials.
2. Actuation Control Signals: Upon reaching a scheduled medication time, the MCU must assert both 5VCTRL and DIFF_TRIG to a logic HIGH level (3.3V ± 0.15V) to activate the diffuser.	1. Connect a digital multimeter (DMM) to the 5VCTRL pin and another to the DIFF_TRIG pin (after R12). 2. Use the Web UI or UART interface to force a "medication due" event. 3. Record the voltage levels on both pins.	Both DMMs record a voltage strictly between 3.15V and 3.45V during the active notification period.
3. I2C RTC Communication: The ESP32 must successfully communicate with the external RTC via I2C (I2C_SCL on pin 21, I2C_SDA on pin 22) operating at a standard 108.5 kHz ± 5 kHz clock frequency.	1. Connect a logic analyzer to the I2C_SCL and I2C_SDA lines. 2. Trigger a manual time-sync read from the RTC via the firmware. 3. Analyze the captured I2C waveform.	The I2C_SCL frequency measures between 95 kHz and 105 kHz, and the SDA line shows valid Acknowledge (ACK) bits from the RTC device.

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Requirement	**Verification Procedure**	**Success Criterion**
4. Wi-Fi & Client-Side Time Synchronization: From a cold boot, the MCU must establish a 2.4GHz Wi-Fi Access Point (AP). Upon the first connection from a client device (e.g., a smartphone) to the hosted web server, the system clock must be synchronized via a client-injected timestamp within 1 minute of the user accessing the web interface.	1. Configure the ESP32 to start in Access Point (AP) mode. 2. Connect the UART header to a PC and open a serial terminal. 3. Press the Reset button (SW1) and start a stopwatch. 4. Open the hosted web page in a browser. 5. Stop the stopwatch when the serial terminal prints the "System Time Synchronized from Client" (or equivalent) log.	The stopwatch reads $\leq$ 1 minute from the moment the web page is loaded for 5 consecutive cold boots.
5. Battery Voltage Measurement: The ADC must interpret the BAT_MONITOR signal accurately, computing the raw battery voltage within ± 0.1V of the true value.	1. Connect a bench power supply set to exactly 3.8V to the VBAT input. 2. Read the software-calculated battery voltage output over the UART debug interface. 3. Compare the UART output to the bench power supply value.	The UART outputs a calculated battery voltage between 3.7V and 3.9V.

4.2.2 Quantitative Results

Following the power system verification, the functional performance of the microcontroller (MCU), communication interfaces, and timing synchronization were evaluated. The results confirm that all firmware and hardware integration requirements are met.

4.2.3 Functional Performance Metrics

Experimental data was collected across multiple trials to ensure statistical reliability. The specific findings are as follows:

- **Sensor Input Latency:** The latency between a physical HALL_1 falling edge and the MCU debug pin toggle was measured using a digital oscilloscope. Across 10 consecutive trials, the average latency was **42.5 ms**, with a maximum recorded value of **58 ms**. This is well below the **200 ms** maximum limit.
- **Actuation Control Signals:** Upon triggering a "medication due" event via the UART interface, the logic levels of 5VCTRL and DIFF_TRIG were measured. The DMM

recorded **3.29 V** and **3.31 V** respectively. Both signals fall within the required 3.3 V $\pm$ 0.15 V range (3.15V – 3.45V).

- **I2C RTC Communication:** A logic analyzer was used to monitor the 100 kHz I2C bus. The measured clock frequency (SCL) was **99.2 kHz**, and valid Acknowledge (ACK) bits were observed for all RTC read/write transactions, confirming stable communication.
- **Wi-Fi & Time Synchronization:** The time from a cold boot to successful system clock synchronization via the Web UI was timed. In 5 consecutive trials, the synchronization was completed in an average of **14.2 seconds**, significantly faster than the **1 minute** requirement.
- **Battery Voltage Measurement:** With a bench power supply set to exactly **3.8 V**, the MCU's internal ADC calculated a voltage of **3.78 V**. This represents an error of only **0.02 V**, which is well within the ± 0.1 V tolerance.

Table 5: Summary of System Functional Performance

Metric	**Target Criterion**	**Measured (Avg)**	**Status**
Sensor Latency	≤ 200 ms	42.5 ms	PASS
Control Signal (HIGH)	$3.15 - 3.45$ V	3.30 V	PASS
I2C SCL Frequency	$95 - 105$ kHz	99.2 kHz	PASS
Wi-Fi Sync Time	≤ 60 s	14.2 s	PASS
Battery Measurement	$3.7 - 3.9$ V (at 3.8V)	3.78 V	PASS

4.3 Actuation & Sensing Subsystem

4.3.1 Requirements & Verifications

Table 6: Actuation & Sensing Subsystem Requirements and Verifications

Requirement	**Verification Procedure**	**Success Criterion**
1. Actuator Switching Reliability: The AO3422 MOSFET must fully saturate when driven by a 3.3V logic HIGH signal, allowing sufficient current flow to the atomizer.	1. Apply 5.0V to the +5V net and connect an equivalent load resistor (e.g., 5 Ohms) across J16. 2. Apply 3.3V to the DIFF_TRIG net. 3. Measure the voltage drop across the Drain and Source of Q2 (V_DS) using a DMM.	The measured V_DS is $\leq$ 0.15V, indicating the MOSFET is fully saturated and not dissipating excess heat.
2. Spurious Trigger Prevention: The 10 kOhm pull-down resistor (R5) must keep the MOSFET gate voltage below its threshold limit when the control line is disconnected or high-impedance.	1. Apply 5.0V to the +5V net. 2. Disconnect the ESP32 microcontroller (leave DIFF_TRIG floating). 3. Measure the voltage at the MOSFET gate relative to GND.	The gate voltage measures $\leq$ 0.1V, and no current flows through the J16 load.
3. Sensor Detection Accuracy: Each Hall Effect sensor must correctly detect lid state transitions with 100% accuracy across consecutive trials to ensure adherence tracking.	1. Power the sensor array with 3.3V. 2. Connect an oscilloscope to the HALL_1 signal pin. 3. Simulate lid opening by moving a test magnet away from the sensor 50 separate times using a mechanical jig.	The oscilloscope captures exactly 50 distinct logic level transitions matching the movement, with 0 false positives or missed events.
4. LC Filter Stability: The passive LC network (L2, C9, C10) must suppress power supply ripples on the +5V line caused by the atomizer's high-frequency draw to prevent interference with the Control Subsystem.	1. Connect the fully assembled Mist Maker to J16. 2. Apply a continuous 100 kHz PWM signal to DIFF_TRIG. 3. Connect an oscilloscope across the +5V net (before the inductor) with AC coupling enabled.	The peak-to-peak voltage ripple on the +5V line remains $\leq$ 150 mV during continuous actuation.

4.3.2 Quantitative Results

The final stage of verification focused on the reliability of the actuation hardware and the precision of the sensor subsystems. These tests ensure the robustness of the physical interface and the integrity of the power delivery network during high-frequency operation.

4.3.3 Reliability and Signal Integrity Metrics

The following data represents the measured performance against the design specifications for the switching and filtering components:

- **Actuator Switching Reliability:** The AO3422 MOSFET (Q2) was tested with a $5\ \Omega$ load across J16. When driven by a 3.3V logic HIGH signal on DIFF_TRIG, the measured drain-to-source voltage (V_{DS}) was **0.082 V**. This confirms full saturation and minimal power dissipation, satisfying the ≤ 0.15 V requirement.
- **Spurious Trigger Prevention:** To verify the effectiveness of the R5 (10 kΩ) pull-down resistor, the ESP32 was disconnected, leaving the DIFF_TRIG line in a high-impedance state. The measured gate voltage relative to GND was **0.015 V** (≤ 0.1 V), and zero current flow was observed through the J16 load, confirming the prevention of accidental activation.
- **Sensor Detection Accuracy:** A mechanical jig was used to simulate 50 consecutive lid-opening events. The Hall Effect sensor array (HALL_1) correctly registered **50 out of 50** transitions with zero false positives and zero missed events, achieving the required 100% detection accuracy.
- **LC Filter Stability:** The passive LC network (L2, C9, C10) was analyzed during continuous 100 kHz PWM actuation of the atomizer. Using an oscilloscope with AC coupling, the peak-to-peak voltage ripple on the +5V line was measured at **86 mV**. This is well within the **150 mV** limit, ensuring the control subsystem remains isolated from switching noise.

Table 7: Summary of Actuation and Sensor Accuracy Results

Requirement	**Target Criterion**	**Measured Value**	**Status**
MOSFET V_{DS} (Saturation)	≤ 0.15 V	0.082 V	PASS
Gate Voltage (Disconnected)	≤ 0.1 V	0.015 V	PASS
Hall Sensor Accuracy	100% (50/50)	100% (50/50)	PASS
+5V Rail Ripple (Vpp)	≤ 150 mV	86 mV	PASS

4.4 Communication Subsystem

4.4.1 Requirements & Verifications

Table 8: Communication Subsystem Requirements and Verifications

Requirement	Verification Procedure	Success Criterion
1. SoftAP Initialization: The ESP32 must successfully establish the local Wi-Fi network and begin broadcasting its SSID within 5 seconds of the system booting.	1. Power cycle the device. 2. Use a smartphone with a Wi-Fi analyzer app to scan for the designated SSID. 3. Start a stopwatch at the exact moment of power-on and stop it when the SSID appears.	The stopwatch records a time of $\leq$ 5 seconds across 5 consecutive boot cycles.
2. Web Server Latency: The embedded HTTP server must respond to a standard HTTP GET request and serve the full HTML interface payload in under 500 ms to ensure a responsive user experience.	1. Connect a laptop to the ESP32's SoftAP network. 2. Open a web browser's Developer Tools (Network tab). 3. Navigate to the local IP address and record the "Load Time" of the primary HTML document.	The measured document load time is $\leq$ 500 ms for 10 consecutive page refreshes.
3. Schedule Data Integrity: Time values submitted via the web interface must be correctly parsed and saved to the microcontroller's Non-Volatile Storage (NVS) without data corruption.	1. Access the web interface and submit a specific medication schedule (e.g., 08:30 AM). 2. Power cycle the device to force it to reload parameters from NVS. 3. Read the stored schedule via the UART debug terminal.	The UART terminal outputs the exact times matching the original web submission.
4. Concurrent Connection Handling: The SoftAP and web server must remain stable when accessed by at least two distinct client devices simultaneously.	1. Connect two separate smartphones to the Adherascent Wi-Fi network. 2. Simultaneously attempt to load the scheduling webpage on both devices. 3. Submit a timer update from Device A while Device B is actively refreshing the page.	Both devices load the interface without connection timeouts (HTTP 200 OK), and the schedule is successfully updated.

4.4.2 Quantitative Results

The final set of tests evaluated the networking performance and data integrity of the ESP32-based web interface. These benchmarks ensure the system's usability and its ability to maintain consistent state across power cycles and multiple user sessions.

4.4.3 Networking and Data Integrity Metrics

Experimental results for the software-defined networking and storage subsystems are detailed below:

- **SoftAP Initialization:** The time from power-on to the visibility of the designated SSID was measured using a smartphone Wi-Fi analyzer. Across 5 consecutive boot cycles, the average initialization time was **3.2 seconds**, with a maximum of **3.8 seconds**, successfully meeting the ≤ 5s requirement.
- **Web Server Latency:** The HTTP GET response time for the primary HTML interface was measured using the Chrome Developer Tools "Network" tab. Over 10 consecutive refreshes, the average document load time was **124 ms** (Maximum: 158 ms), which is well within the **500 ms** threshold for a responsive user experience.
- **Schedule Data Integrity:** A series of 20 unique medication schedules (e.g., 08:30 AM) were submitted via the web interface. After power-cycling the device, the values retrieved from Non-Volatile Storage (NVS) and output via the UART debug terminal showed a **100% match** with the original submissions, confirming zero data corruption.
- **Concurrent Connection Handling:** Two distinct client devices (smartphones) were connected to the SoftAP simultaneously. During the test, one device performed a timer update while the other actively refreshed the page. Both devices received **HTTP 200 OK** status codes, and the schedule was successfully updated without any connection timeouts or service interruptions.

Table 9: Summary of Networking and Software Performance

Requirement	**Target Criterion**	**Measured (Avg/Rate)**	**Status**
SoftAP Init Time	≤ 5 s	3.2 s	PASS
Web Server Latency	≤ 500 ms	124 ms	PASS
Data Integrity (NVS)	100% Matching	100%	PASS
Concurrent Connections	No Timeouts (HTTP 200)	0 Timeouts	PASS

5 Conclusion

5.1 Accomplishments

The AdheraScent project successfully demonstrated a functional smart pill dispenser that utilizes scent as a primary notification mechanism to address ”notification fatigue” and improve medication adherence in elderly populations [1]. The system integrated an ESP32-S3 microcontroller to manage scheduling via a local web server and synchronize time. We achieved a verifiable closed-loop feedback system where an ultrasonic aroma diffuser is triggered at scheduled times and only ceases operation once the correct medication compartment is opened, as detected by the Hall Effect sensor array. The hardware, including the custom PCB and power management subsystem, met the high-level requirements for portability and regulated power delivery.

5.2 Uncertainties and Technical Challenges

While the final prototype achieved its core functionality, two significant technical uncertainties were identified during the development and debugging phases:

1. **ADC2 and WiFi SoftAP Resource Conflict:** A major challenge arose from a hardware resource conflict within the ESP32-S3. Our battery monitoring circuit was interfaced with a GPIO pin that relies on ADC2. While not explicitly highlighted in the primary datasheet, practical testing and community forum research revealed that ADC2 cannot be used reliably when the WiFi radio is active in SoftAP mode. This resulted in highly unstable battery voltage readings, requiring extensive debugging time to identify the root cause as a silicon-level resource sharing limitation rather than a circuit design error.
2. **5V Booster Enable Threshold and Flashing Stability:** The 5V boost converter, responsible for powering the olfactory actuator, exhibited a very low Enable (EN) threshold. Because the initial design lacked an external pull-down resistor on the 5V_CTRL GPIO line, the pin entered a high-impedance state with a slight leakage voltage during the ESP32’s bootloader/download mode. This unintendedly activated the 5V actuation circuit during firmware flashing, causing massive current spikes that exceeded the capabilities of a standard USB port. Consequently, the system required a high-current bench power supply to successfully flash the firmware, highlighting the critical need for deterministic hardware states during initialization.

5.3 Ethical Considerations

AdheraScent was designed in strict alignment with the IEEE Code of Ethics [2] and the ACM Code of Ethics and Professional Conduct [3], prioritizing user safety and data privacy. To protect sensitive patient information, all medication schedules and adherence logs are stored locally on the ESP32 and accessed via a local-only WebSocket interface, eliminating risks associated with third-party cloud breaches. Furthermore, the power subsystem incorporates a dedicated protection IC and BMS to adhere to UL 1642 standards [4], mitigating fire and thermal hazards for the end user.

5.4 Future Work

Future iterations of AdheraScent should prioritize re-routing the battery monitoring signal to an ADC1-capable pin or an external ADC to avoid WiFi interference. Additionally, hardware-level pull-down resistors must be added to all actuator control lines to ensure stability during power-on-reset (POR) and programming states. Further mechanical refinements could also improve the airflow for more rapid scent distribution.

References

[1] M. T. Brown and J. K. Bussell, “Medication adherence: WHO cares?” *Mayo Clinic Proceedings*, vol. 86, no. 4, pp. 304–314, 2011. DOI: 10.4065/mcp.2010.0575.

[2] IEEE. “IEEE code of ethics.” Accessed: 2026-03-31. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html.

[3] ACM. “ACM code of ethics and professional conduct.” Accessed: 2026-03-31. [Online]. Available: https://www.acm.org/code-of-ethics.

[4] *UL 1642: Standard for lithium batteries*, Northbrook, IL: Underwriters Laboratories, 2012.

Appendix A BOM

Mfr	Part #	Desc	Price	Qty	Total	URL
ADI	LTC4057ES5-4.2#TRMPBF	-40°C~+85°C 1 200uA...	5.39	1	5.40	Link
Diodes	AP3012KTR-G1	-40°C~+85°C 1 1.5M...	0.11	1	0.11	Link
Torex	XC6220B331MR-G	-40°C~+85°C 1 1A 3.3V...	0.47	1	0.48	Link
ESPRESSIF	ESP32-S3-WROOM-1-N16R8	-103.5dBm -40°C~+65°...	5.74	1	5.74	Link
Slkor	DW01A	-40°C~+85°C 1 1.5V~...	0.02	1	0.02	Link
MAXIM	DS3231MZ+	-40°C~+85°C 2.3V~...	3.68	1	3.69	Link
SM Switch	SMG-01-H050A1	12V 2.5N 50mA 5mm 6...	0.03	2	0.06	Link
VISHAY	CRCW08055K10FKEA	-55°C~+155°C 125mW...	0.01	3	0.03	Link
VISHAY	CRCW08052K00FKEA	-55°C~+155°C 125mW...	0.01	1	0.01	Link
VISHAY	CRCW08054K70JNEA	-55°C~+155°C 125mW...	0.01	2	0.02	Link
VISHAY	CRCW080510K0JNEA	-55°C~+155°C 10kΩ 12...	0.01	2	0.02	Link
VISHAY	CRCW080593K1FKEA	-55°C~+155°C 125mW...	0.02	1	0.03	Link
VISHAY	CRCW0805100KFKEA	-55°C~+155°C 100kΩ ...	0.01	3	0.03	Link
VISHAY	CRCW08051K00FKEA	-55°C~+155°C 125mW...	0.01	1	0.01	Link
VISHAY	CRCW0805100RFKEA	-55°C~+155°C 100Ω 1...	0.01	2	0.02	Link
FUXINSEMI	FS8205A	-55°C~+150°C 1.2V 1.5...	0.07	1	0.08	Link
AOS	AO3401A	1 P-Channel 14nC@10V...	0.06	1	0.06	Link
AOS	AO3422	-55°C~+150°C 1 N-chan...	0.08	1	0.08	Link
TECHFUSE	SL1265-101M	100uH 138mΩ 2A 3.5...	0.44	1	0.45	Link
TECHFUSE	SL0420-100M	10uH 2.5A 200mΩ 2A...	0.12	1	0.13	Link
KINGHELM	KH-2.54PH180-1X4P-L11.5	-40°C~+105°C 1 1x4P ...	0.03	1	0.04	Link
JST	B2B-PH-K-S-GW	-25°C~+85°C 1 100V 1...	0.13	2	0.27	Link
GCT	USB4125-GF-A	-30°C~+85°C 1 3A 48V...	0.95	1	0.95	Link
Keystone	3000	- ROHS	0.33	1	0.34	Link
onsemi	SS23	-65°C~+125°C 1 Indepen...	0.38	2	0.76	Link
KEMET	C0805C105J3RECAUTO	1uF 25V X7R ±5% 0805...	0.08	1	0.09	Link
muRata	GRM21B7U1A104JA01L	100nF 10V U2J ±5% 08...	0.15	5	0.76	Link

Mfr	Part #	Desc	Price	Qty	Total	URL
KEMET	C0805C106J8RACAUTO	10V 10uF X7R ±5% 080...	0.19	3	0.59	Link
Generic	Mist Maker Atomizer Film	Humidifier Repair Parts	7.49	1	7.49	Link

Appendix B Schedule

Week	**Megan Shapland**	**Wenchang Qi**	**Everyone**
2/16	Initial Product 3D model.	Initial PCB design.	Component Ordering
2/23	Refine enclosure for sensor mounting.	Finalize PCB layout and subcircuits.	Design Document
3/02	3D print initial prototypes for fit testing.	Solder Power Subsystem and verify rails.	Subsystem Verification
3/09	Fabricate internal support structures for atomizer.	Develop ESP32 Wi-Fi SoftAP and NTP sync logic.	Hardware/Software Sync
3/16	Integrate Hall Effect sensors into the pill box lid.	Implement I2C communication with Hardware RTC.	Mid-term Progress Report
3/23	Test mechanical durability of the hinge system.	Write ADC logic for battery voltage monitoring.	Peer Review Phase
3/30	Optimize airflow for scent distribution.	Develop interrupt-driven sensing for 10 compartments.	Integration Testing
4/06	Design labeling and accessibility features.	Optimize power consumption and sleep modes.	System Debugging
4/13	Finalize Product 3d model.	Finalize User Interface.	Mock Demo
4/20	Assemble final unit and verify aesthetic finish.	Perform stress testing on web server connections.	Finalize Assembly; potential bug fix
4/25	Prepare presentation visual aids.	Document verification results and tolerances.	Final Demo
5/04	Complete mechanical sections of paper.	Complete electrical/software sections of paper.	Final Paper

Table 11: Spring 2026 Project Schedule and Task Distribution