

ADHERASCENT

By

Albert Liu (ycl6)

Anshul Rao (anshulr2)

Chia-Ti Liu (chiatil2)

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TA: Zhuchen Shao

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Contents

- 1. Introduction..... 3
 - 1.1 Problem..... 3
 - 1.2 Solution..... 3
 - 1.3 Visual Aid..... 4
 - 1.4 High-level requirements list.....5
- 2 Design..... 7
 - 2.1 Block Diagram.....7
 - 2.2 Subsystem Overview..... 7
 - 2.3 Subsystem Requirements..... 9
 - 2.4 Tolerance Analysis..... 10
- 3. Ethics, Safety and Societal Impact.....12
 - 3.1 Ethics..... 12
 - 3.2 Safety and Regulatory Standards.....12
 - 3.3 Societal Impact..... 12
- References..... 14

1. Introduction

1.1 Problem

The modern healthcare faces a “silent epidemic” that occurs after the patient leaves the hospitals or clinics: the failure to execute prescribed care. Even though medical diagnostics have advanced rapidly, the actual execution of care remains a significant failure point. As of 2026, approximately 50% of patients with chronic conditions fail to follow their prescribed treatment plan [1]. For most people, this is not a deliberate choice but a result of cognitive overload. Forgetfulness is the most frequent barrier, cited by 62 % of non-adherence patients [2], a struggle caused by the rise of “polypharmacy” where individuals must manage complex schedules involving five or more daily medications [3]. This gap in care is extremely acute for the one in four adults report experiencing memory loss or cognitive interference with daily tasks [4], making the development of automated adherence tools a critical necessity for maintaining public health and safety.

This widespread non-adherence presents a severe threat to public welfare and safety. Medication errors and missed doses lead to approximately 125,000 preventable deaths annually in the United States [5]. Beyond mortality, non-adherence is a primary driver of system-wide safety risks, currently linked to up to 25% of all hospital admissions [6]. Since consistent dosing is fundamental to controlling conditions like hypertension and diabetes, improving adherence is now recognized as a top public health priority, essential for reducing morbidity and ensuring that medical interventions achieve their intended life-saving outcomes.

The implications of this problem extend to global economic and environmental factors. Economically, non-adherence drains the U.S. healthcare system of \$100 billion to \$300 billion every year in avoidable emergency visits and complications [7]. Environmentally, suboptimal adherence is a major driver of pharmaceutical waste, contributing to a healthcare carbon footprint that accounts for nearly 5% of global greenhouse gas emissions [1]. Socially, the burden often falls on family caregivers who experience significant emotional and physical strain while managing the repercussions of a patient’s missed doses [6]. By addressing the technical barriers to medication timing, this project aims to mitigate these broad societal costs while promoting a more sustainable and effective model of care.

From an engineering perspective, the challenge lies in developing a reminder mechanism that is

- Independent of smartphones or external connectivity
- Physically present in the user’s environment
- Difficult to ignore yet non-disruptive
- Energy-efficient for long-term battery operation
- Safe for use around medication storage

1.2 Solution

The proposed solution, AdheraScent, is a battery powered pillbox that integrates time-based monitoring, compartment open and close detection, and a controlled scent emission mechanism to provide adaptive medication reminders.

The system would continuously monitor scheduled medication windows with a real-time clock integrated with an ESP32 microcontroller. Each daily compartment of the 7-day pill container is equipped with an open/close sensor to determine whether medication has been accessed during its assigned time window. If the container remains closed after the scheduled window expires, the control unit activates the scent emitter.

The scent emission subsystem consists of a replaceable scent pad, a mechanically controlled airflow path, and a variable-speed DC fan. When triggered, airflow is enabled across the scent pad to release scent into the environment. The emission intensity is modulated using pulse width modulation (PWM), allowing gradual increases in scent if the medication is still missed. Once the container is opened, the emission will stop immediately.

To ensure long-term reliability, the system assumes a predetermined scent pad lifetime (e.g. 20 days). The microcontroller tracks elapsed time since installation of the scent pad and activates a blinking LED when the pad approaches the end of its effective service life. The system operates without smartphone integration and employs power management to extend battery life.

1.3 Visual Aid

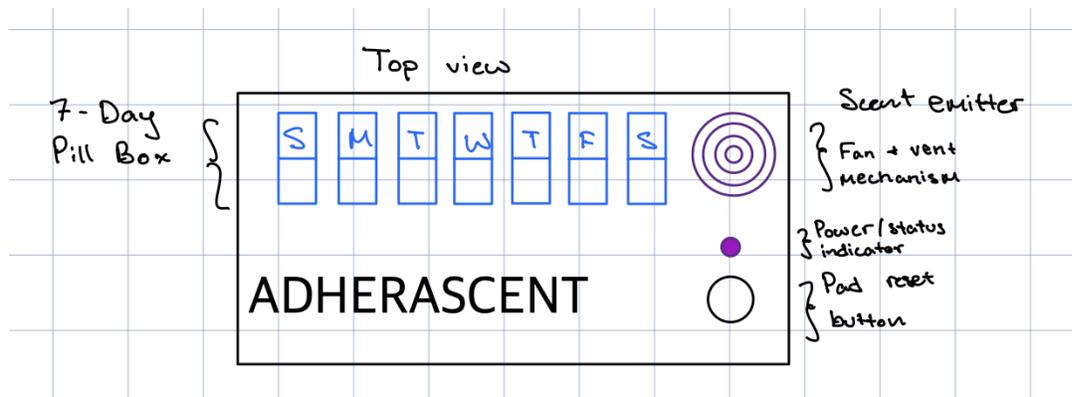


Figure 1 AdheraScent System Top view. This perspective shows the layout of the seven pill compartments and the scent-dispensing vents with chassis.

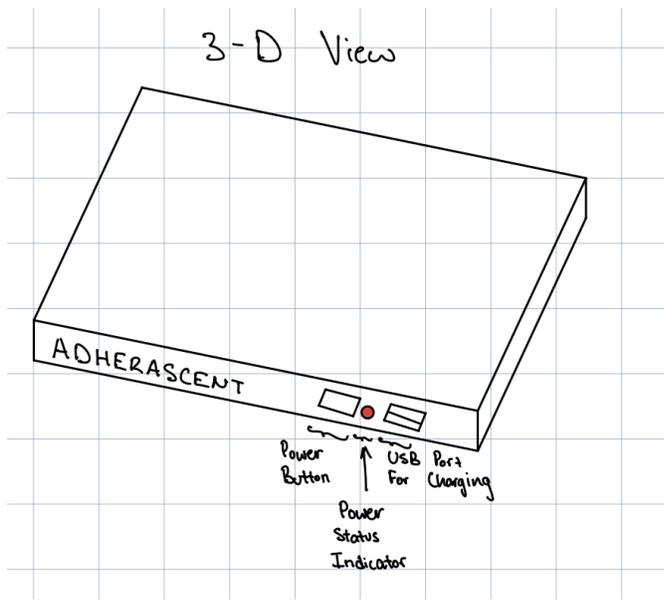


Figure 2 AdheraScENT System 3D view. This view demonstrates the overall form factor and the primary user interface area.

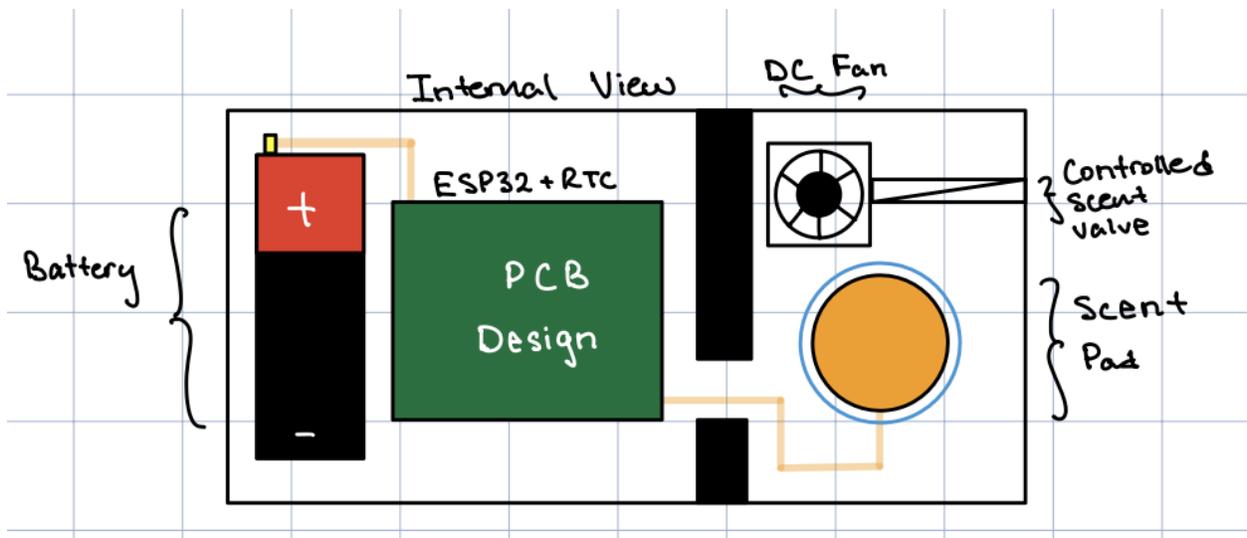


Figure 3 AdheraScENT System Internal view. This view reveals the spatial allocation of the ESP32, the Timing Control Unit, and the mechanical components of the Scent Emitter Subsystem.

1.4 High-level requirements list

Functional Requirements

- The system correctly detects whether the pill container has been opened during a scheduled medication window.
- The user must be able to schedule a medication window.
- The scent emitter must activate within 10 seconds automatically after the scheduled medication window has passed if the pill container has remained in a closed state.

- This scent-based pill reminder system must have variable amounts of scent intensity as the duration of the missed medication window increases based on the PWM signal (25%, 50%, 100%).
- The scent emitter deactivates within 10 seconds once the container is opened.
- LED starts blinking when replaceable scent pad has to be changed and stops after its replaced.
- The system operates without requiring a smartphone, app, or external display.
- The device operates reliably for multiple medication cycles without failure.
- All subsystems integrate into a single functional prototype suitable for demonstration.
- The prototype has to be smaller than $5 \times 2.8 \times 0.5$ inch³ to allow it to be portable.
- Scent strong enough for real-world testers to recognize.
- Power consumption of the system to be small enough to allow the device to function for longer than 2 months before the battery has to be replaced.

2 Design

2.1 Block Diagram

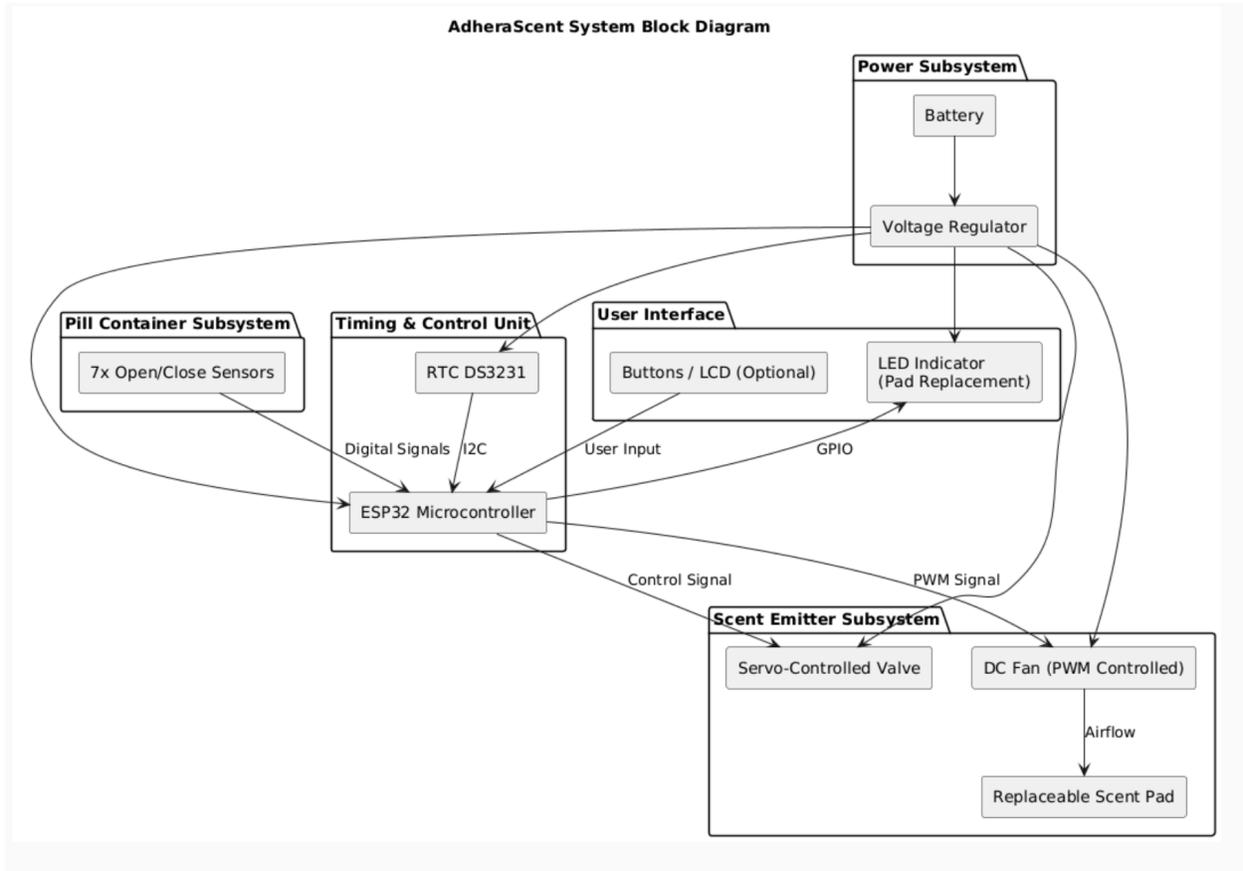


Figure 4 AdheraScent System Block Diagram. This diagram illustrates the high-level architecture of the pillbox, detailing the interconnections between the Power Subsystem, Timing & Control Unit (featuring the ESP32 and RTC DS3231), and the Scent Emitter output stage.

2.2 Subsystem Overview

The AdheraScent pill box reminder system primarily uses 5 tightly integrated physical subsystems to help an individual take their medication as directed on a timely and consistent basis using olfactory reinforcement. These subsystems work in a consistent feedback loop. The timing and control subsystem manages the medication schedule; the pill container subsystem detects when containers are opened or closed; the scent emitter subsystem delivers and adjusts the intensity of the sensory reminder; the power subsystem supplies the necessary energy to the device; the user interface subsystem allows users to configure the device settings and monitor system status.

2.2.1 Power

The power subsystem supplies energy to all modules in the device. A battery provides the primary supply, which is regulated into stable voltage rails required by the electronics. The ESP32 and the RTC would be operating from a regular 3.3V rail, while the fan and valve actuator may require a 5V rail depending on selected components. A power switch will also be allowing the user to fully disconnect system power.

2.2.2 Timing and Control

The timing and control subsystem is the core logic unit of our device. This design utilizes a ESP32 as the main microcontroller and an RTC DS3231 module to measure global time. The ESP32 will read realtime time from the RTC DS3231 over I2C and also compares it against the scheduled medication windows. It will also continuously monitor the pill container sensor GPIOs to also determine if medication has been taken. If a missed-dose event occurs, the ESP32 will output control signals to the scent emitter subsystem.

2.2.3 Pill Container

The pill container subsystem will physically store medication and detect whether each day's compartment has been opened. The seven sensors, which is one per compartment, will output digital signals to the ESP32 GPIO inputs, and these signals will be used by the Timing and Control Subsystem to determine whether the user accessed the medication during the scheduled window. At the same time, the 7 sensors also provide the signal to terminate the scent emission when a container is opened.

2.2.4 User Interface

The user interface subsystem provides an interaction for configuration and feedback and utilizes a pad schedule button and a status LED to display to the user. The schedule button sends an input signal to the ESP32 to support scheduling. The status LED is driven by an ESP32 output to indicate the scent pad replacement after a predetermined lifetime threshold.

2.2.5 Scent Emitter

The scent emitter subsystem should provide the physical reminder mechanism. This subsystem utilizes a scent pad, a fan to dissipate the scent, and a valve actuator to control the intensity of the scent. When it is triggered by the ESP32, a valve actuator opens an airflow path and the DC fan runs at a controlled speed to push air across the replaceable scent pad. It also increases the reminder intensity as time passes after the missed window with an increasing PWM duty cycle. The subsystem will stop the emission when the ESP32 deactivates the fan and closes the valve when it detects that the pill container has been opened.

2.3 Subsystem Requirements

2.3.1 Power

This subsystem satisfies the high-level requirements of portability and a ≥ 2 months of battery life.

Interface:

- Voltage of battery to regulators
- Regulated outputs of 3.3V rail for logic and 5V rail for fan.

Requirements:

- The power subsystem shall provide 3.3V to ESP32, RTC, User Interface.
- Provide 5V to the fan and valve actuator.
- The power switch should disconnect the voltage of the battery from the rest of the system with negligible leakage when it is off.

2.3.2 Timing and Control

This subsystem satisfies the high-level requirements of scheduled monitoring, monitoring, miss medicine detection, scent pad lifetime tracking, and scent shutoff upon opening. Without it, the system cannot implement conditional logic or timing.

Interfaces:

- RTC interface
- Sensor inputs: 7 GPIO digital inputs.
- Outputs: GPIO to LED, and PWM to fan and valve actuator.

Requirements:

- It should maintain time using the DS3231 RTC and retain correct time across power interruptions.
- It will allow one daily scheduled medication window to be configured and stored.
- If the pill container remains closed after the scheduled window ends, the subsystem will trigger scent emission in 10 seconds.
- The subsystem will provide three fan intensity levels and increase intensity as missed time increases.
- When any compartment is opened, the subsystem will turn off the fan and also close the valve in 10 seconds.
- It will track scent pad age and trigger the LED warning threshold at day 15 of a 20-day pad life (We can

2.3.3 Pill Container

The subsystem will enable the high-level requirements of detecting whether medication was taken and turning off scent emission when the container is opened.

Interfaces:

- Output to ESP32: digital GPIO logic compatible with 3.3V input level
- Detection latency: open events must be detectable within 1 seconds.

Requirements:

- Each of the compartment sensors should provide a stable digital state representing OPEN and

CLOSED to the ESP32.

- Sensor outputs should include debounce to avoid false transitions.

2.3.4 User Interface

This subsystem should satisfy the requirements of no smartphone or app, and only with a little LED for pad replacement notifications.

Interfaces:

- Button: GPIO digital input.
- LED: GPIO output.

Requirements:

- The schedule button should provide reliable input to ESP32 with press detection and debounce.
- The status LED should be visible in normal indoor lighting.
- The LED should indicate pad replacement by blinking when pad age exceeds the warning threshold, and when the pad is replaced, it should stop blinking in 10 seconds.
- The User Interface should function with no external device.

2.3.5 Scent Emitter

This subsystem will satisfy the high-level requirements of providing physically present reminder with increasing intensity and will stop immediately when any compartment is opened.

Interfaces:

- Fan control: PWM input
- Valve control: PWM driven actuator

Requirements:

- The subsystem should support continuous scent emission when it is enabled, and it should be able to operate at 3 intensity levels.
- The fan should produce airflow across the scent pad when it receives the signal.
- The valve actuator should open and close the airflow path.
- When it should be disabled, the subsystem should stop the scent emission within 10 seconds when any compartment is detected to be opened.
- The scent pad should be easily replaceable for users.

2.4 Tolerance Analysis

The primary risk to the successful operation of the pillbox is temporal desynchronization. The system relies on the ESP32's internal crystal oscillator to track elapsed time between the "close" and "open" states of the box. If this clock drifts significantly, the scent-based notification may trigger outside of the prescribed medical window, leading to user confusion or missed doses.

To demonstrate the feasibility of using the ESP32 without an external Real-Time Clock (RTC), we must analyze the Worst-Case Drift (ΔT). A standard ESP32 crystal oscillator has a frequency tolerance (ϵ) of approximately ± 100 ppm (parts per million).

For a standard 24-hour medication cycle ($T_{total} = 86400\text{ s}$). The maximum deviation is calculated as:

$$\Delta T = 86400\text{ s} * (100 * 10^{-6}) = 8.64\text{ seconds per day} \quad (1.1)$$

Even under varying thermal conditions – such as the heat generated by the scent-emission motor – where the tolerance might degrade to $\pm 500\text{ ppm}$, the drift is calculated as:

$$\Delta T_{worst} = 86400\text{ s} * (500 * 10^{-6}) = 43.2\text{ seconds per day} \quad (1.2)$$

The feasibility of this design is confirmed by comparing the hardware error to the functional requirements of medication adherence:

Safety Margin: Medical experts generally define a “missed dose” window as 30 to 60 minutes past the scheduled time. Our worst-case hardware drift of 43.2 seconds represents only 0.05% of a 24-hour cycle, or roughly 2.4% of the most conservative (30-minute) medical grace period.

Cumulative Error Mitigation: To ensure long-term feasibility, the software will utilize the ESP32’s Wi-Fi capabilities to perform an NTP (Network Time Protocol) sync once every 24 hours. This “resets” the accumulated drift to zero, ensuring that the error never exceeds the sub-minute daily maximum.

The analysis confirms that the internal timing tolerance of ESP32 is sufficient for the pillbox’s mission. The hardware error is orders of magnitude smaller than the acceptable human-factor window for medication intake.

3. Ethics, Safety and Societal Impact

3.1 Ethics

As engineers, we have a professional responsibility to prioritize the safety and welfare of the public, as outlined in IEEE Code of Ethics 1.1. The primary ethical concern for this project is the reliability of the olfactory alert and the open-detection logic. Since the device is intended to assist with medication management, any failure of the scent-release mechanism or a false “completed” reading (incorrectly sensing the box as open) could lead to a missed dose and subsequent health complications. To avoid ethical breaches regarding IEEE Code 1.3 (Honesty and Transparency), we will clearly state the device’s scope: it is an assistive notification system, not a dispensing system that guarantees ingestion. Furthermore, per ACM Code of Ethics 1.6, all data regarding the user’s medication timing – even if the user manually fills the box – will be treated as sensitive personal health information and protected from unauthorized access.

3.2 Safety and Regulatory Standards

To ensure the safety of our engineering solution, we have identified several potential risks with the scent-based notification and physical interaction. A primary safety concern is system logic or sensor failure, where the device fails to accurately detect the open/closed state of the medication compartment. If the sensor fails to register that the user has accessed their medication, the system may incorrectly continue to trigger alerts or fail to record the adherence data, leading to confusion and double dosing. To mitigate this, our design will include redundant sensor checks and a visual status indicator (such as an LED) to confirm to the user that their action was successfully recorded. Secondary to technical failure is the risk of accidental misuse, such as the user failing to fully close the box. To address this, the system will be programmed to trigger a ‘re-close’ alert if the compartment remains open for an extended period, ensuring the device remains ready for the next scheduled window.

Regarding the olfactory mechanism, we will ensure that all aromatic materials used are non-toxic and comply with consumer safety standards to prevent respiratory irritation or allergic reactions. During development, we will adhere to IEC 60601-1 standard [8] for medical electrical equipment to ensure the components powering the scent release are properly insulated to prevent fire or shock hazards. The project will also comply with campus safety policies and FCC regulations regarding wireless interference if Bluetooth is utilized for data logging.

3.3 Societal Impact

The impact of this engineering solution extends far beyond the individual user. Societally, this scent-based notification system aims to restore autonomy to adults managing medical conditions by a non-invasive, dignified reminder that doesn’t rely on loud alarms or complex digital interfaces. By promoting independence, the device significantly reduces the caregiver burden – the emotional and physical strain placed on family members who must currently supervise medication schedules.

From an economic perspective, improving adherence addresses a major drain on the U.S. healthcare system, which currently spends between \$100 billion and \$300 billion annually on avoidable emergency visits and complications [7]. Finally the project has a positive environmental impact by reducing

pharmaceutical waste. By ensuring medications are used as intended rather than discarded, we help mitigate a source of pollution that contributes to the healthcare sector's carbon footprint, which currently accounts for nearly 5% of global greenhouse gas emissions [1].

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