FadeX: Automated Nicotine Tapering Device

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1 Introduction

1.1 The Problem

Electronic cigarettes were originally marketed as cessation tools, yet they have become a primary source of addiction. Current cessation methods like gum or patches fail to address the "oral fixation" habit, leading to high relapse rates. While nicotine replacement therapies such as patches and gum exist, they do not address behavioral reinforcement mechanisms such as inhalation rituals and oral fixation. These habits are strongly associated with relapse.

Alternatively, "manual tapering" (buying bottles with progressively lower nicotine) is logistically difficult and prone to user error; users often relapse when they cannot find the specific lower concentration they need or struggle with the "cold turkey" steps between available concentrations (e.g., jumping from 5% down to 3%). There is currently no device that automates the tapering process while maintaining the user's behavioral routine.

This issue intersects with public health, addiction science, and consumer safety. A device that enables controlled nicotine reduction while maintaining behavioral continuity may reduce from happening, and improve cessation outcomes. However, such a device must include robust safety interlocks and dosage limits to prevent harm or misuse.

1.2 Our Solution

FadeX is a Bluetooth-enabled vaporization device that automates nicotine reduction. Unlike standard devices, FadeX utilizes a dual-reservoir system: one pod containing high-concentration nicotine and another containing zero-nicotine dilutant.

The device features an active mixing system using micro-peristaltic pumps driven by an ESP32 microcontroller. Based on a schedule set in the companion mobile app, the device calculates and delivers a specific ratio of liquids to the heating element in real-time. This allows for a continuous reduction in nicotine that is harder for the user to perceive (e.g., 5.0% to 4.9% to 4.8%) rather than distinct steps.

The system includes pod authentication to ensure safe liquid usage and strict software fail-safes to limit dosage per hour. It would also implement safety protocols in regards to temperature, and have a charge-capability similar to that of current e-cigarettes.
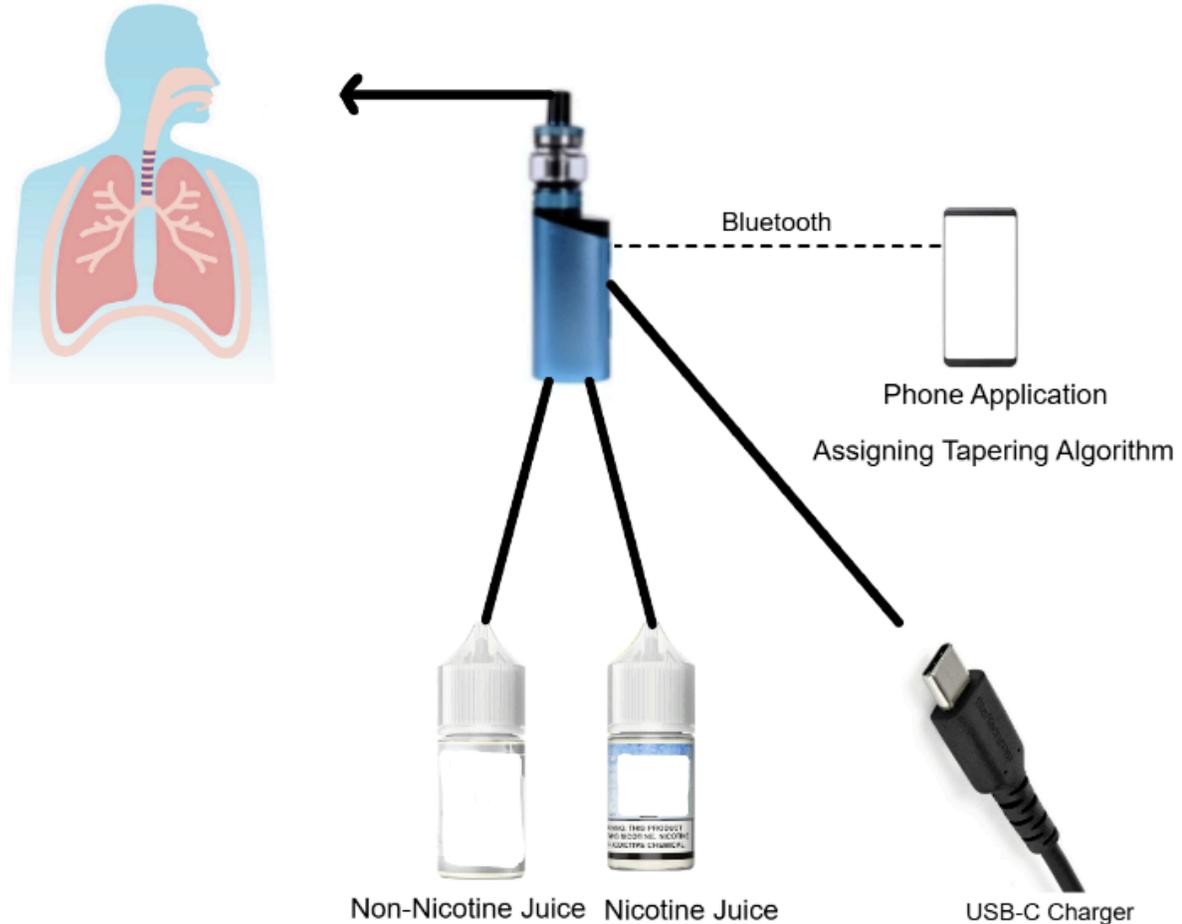
1.3 Visual Aid:

Figure 1: High-level diagram of the FadeX vape external system

1.4 High Level Requirements:

- Automatic wireless control of the system through a preset algorithm implemented on a software application. This application will be able to interface with the user to control the pace at which the nicotine reduction is happening. The MCU will be recording crucial information for analytics to be displayed on the application so the user is aware of their habits. The algorithm will be able to record how many uses over an arbitrary period of time.
- Accuracy of mixing nicotine liquid and dilutant with an error of less than 20%. The concentration of nicotine will be measured using a sensor in the main chamber, which is fed by a liquid micro-pump system from two separate tanks. This value may seem high, but in laboratory environments, industry standards allow for around a 10% tolerance, so for our design, we allowed for more room for error. The goal will be to do much better than this.
- The firmware must enforce a maximum nicotine delivery cap, based on puff duration and current nicotine concentration. The user should not be able to "cheat" the system, so a limit must be placed by tracking the active inhale time and comparing it with the predetermined limit.
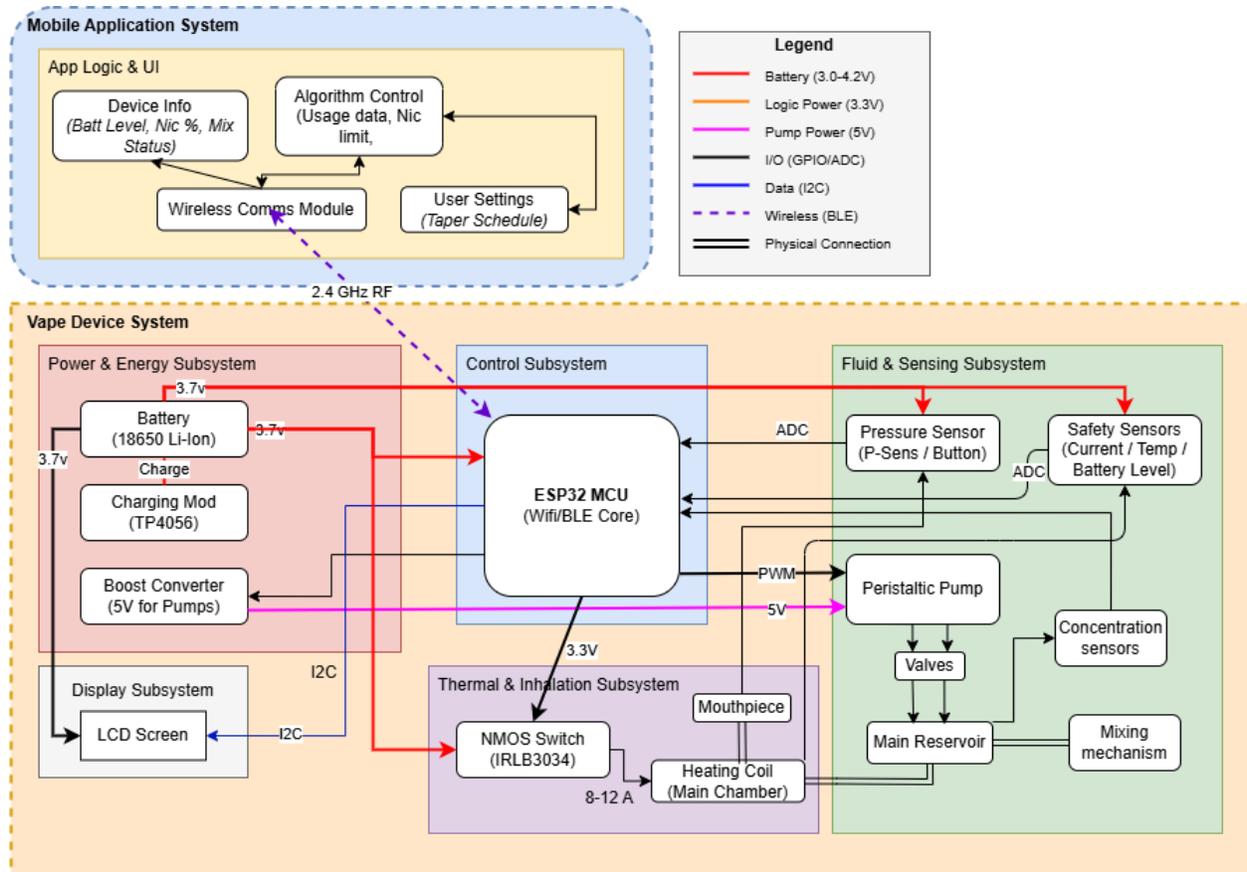
2. Design

2.1 Block Diagram:

Figure 2: Block diagram of the FadeX vape and software system design

2.2 Subsystem Overview:

- Power & Energy Management: Supplies regulated 5V and 3.3V rails from a single-cell 18650 Li-ion battery. Include charging circuitry(TP4056), battery monitoring, and power budgeting logic. Provides stable voltage to pumps, MCU, sensors, and heating element driver.
- Fluid, Mixture & Sensing: Controls two DC micro-peristaltic pumps (like the Kamoer NKP series) to meter nicotine and diluent into a mixing chamber. PWM duty cycles determine flow rate ratios.
- Thermal & Aerosol Generation: Uses a 1 Ohm Kathal coil driven via IRLB3034 MOSFET. A pressure sensor detects inhalation events and switches on the coil. If the coil circuit exceeds a set current over time rating then the ESP32 will stop driving the IRLB3034 MOSFET.

- Control, Display & Connectivity: ESP32 microcontroller executes taper algorithm, enforces safety constraints, logs usage data, and communicates via bluetooth. LCD display provides a dashboard that shows real-time feedback including concentration level, battery level, and puff count.

2.3 Subsystem Requirements :

- Power & Energy Management:
  - This subsystem converts energy from a single-cell 18650 Li-ion battery into reliable rails for the ESP32, sensor, pumps, and UI, and it safely recharges the cell. It directly ensures a safe operation by preventing things like voltage drops and unsafe charging behavior.
  - Inputs:
    - Battery: Single-cell 18650, 3.6-3.7 nominal range
    - Charge input: 5V USB into charger module
  - Output:
    - Logic rail: 3.3V $\pm$ 0.05 V, continuous $\geq$ 300 mA
    - High-current path to coil: battery direct or boosted rail supporting peak $\geq$ 8-12 Amps for $\leq$ 5 seconds
  - Interfaces:
    - Battery voltage sense to ESP32: measurable range 2.8-4.3 V
    - Charger current limit: $\leq$ 1 A charge current
  - Requirements:
    - Must provide 3.3 V $\pm$ 0.05 V at $\geq$ 300 mA continuously to prevent ESP32 resets during bluetooth and display use.
    - Must support peak coil current $\geq$ 8 A without tripping protection or causing rail collapse.
    - Must prevent discharge below 2.8 V to avoid damage to the battery
    - Must safely charge the cell from 5 V input current limiting $\leq$ 1 A
    - Must include overcurrent protection such that a short does not exceed 15 A for more than 50 ms
- Control, Safety Logic & Connectivity:
  - This subsystem executes the tapering algorithm, enforces firmware safety limits, controls pumps and coil firing, and communicates with the phone app via bluetooth. It ensures the high level requirements for autonomous tapering, lockout enforcement, and pod safety interlocks.
  - Inputs:
    - 3.3 V power rail
    - Puff detection sensor
    - Temperature feedback
    - Pod authentication
    - User inputs(buttons) and commands
  - Output:

- ■ PWM/GPIO control to pump driver
- ■ Coil fire control to NMOS gate
- ■ User interface outputs
  - ○ Interfaces:
    - ■ Bluetooth link: target range $\geq$ 2m
    - ■ Cyclic Redundancy Check
    - ■ Nonvolatile memory
  - ○ Requirements:
    - ■ Must enforce a nicotine delivery cap of 1 mg per hour by tracking puffs, and lock out nicotine path once exceeded
    - ■ Must disable coil firing if measured temperature exceeds 250 degrees celsius
    - ■ Must maintain bluetooth communications with encrypted pairing to prevent unauthorized schedule modifications

- ● Fluid, Mixture & Sensing:
  - ○ This subsystem stores nicotine and diluent fluids in separate pods and drives them to a mixing chamber using two micro pumps. It also detects puff events and provides the primary input used to trigger dosing. It directly supports the high level requirement of mixing and enables autonomous tapering.
  - ○ Inputs:
    - ■ Nicotine pod fluid, diluent pod fluid
    - ■ Pump power rail
    - ■ PWM from ESP32 to pump driver
  - ○ Output:
    - ■ Mixed liquid delivery to the atomizer
    - ■ Puff detection signal to the ESP32
  - ○ Interfaces:
    - ■ Pump flow range
    - ■ Ratio control
    - ■ Puff detection
  - ○ Requirements:
    - ■ Must achieve commanded concentration with a reasonable margin of error
    - ■ Must detect a puff within $\leq$ 100 ms of inhalation start to avoid delayed or unintended dosing
    - ■ Must confirm pod presence and slot assignment before dosing, and missing pod must force a state of inactivity

- Thermal & Aerosol Generation:
  - This subsystem converts the mixed liquid into vapor using a resistive heating coil. It must do so consistently and safely. It directly supports the high level safety requirement by ensuring temperature limits and keeping vapor output stable across puffs.
  - Inputs:
    - Mixed liquid feed
    - Puff detection sensor
    - Battery high-current path
    - NMOS gate signal from ESP32
    - Temperature feedback via NTC thermistor
  - Output:
    - Vapor generation
    - Temperature reading back to control subsystem
  - Interfaces:
    - Coil resistance: 1 ohms $\pm$ 20%
    - Puff detection using pressure sensor or button
    - Overtemperature threshold: 250°C
    - Max firing duration: $\leq$ 5 seconds per puff, enforced in firmware
  - Requirements:
    - Must generate vapor with repeatable output: coil power must be within $\pm$15% of target during firing
    - Must provide temperature sensing with enough resolution to detect a 10 degree celsius rise and shut down if open/shorted
    - Must shut down coil within $\leq$ 50 ms of detecting overtemperature or fault
    - Must safely charge the cell from 5 V input current limiting $\leq$ 1 A
    - Must electrically isolate control logic from coil current path using an NMOS rated for $\geq$30 V and A

- Mobile Application System:
  - This subsystem allows users to interface with the device via a mobile application. Specifically, it gives the user the ability to control their tapering algorithm to fit their desired pace of nicotine reduction. It also delivers important control features and analytics.
  - Inputs:
    - Battery level
    - Reservoir Status (Empty/Level)
    - Use count
  - Output:
    - ESP 32 MCU tapering algorithm setpoints
    - User control signals

- Interfaces:
    - The user
    - Bluetooth to send/receive information to/from the ESP32 MCU
    - Storing local data onto smartphone
- Requirements:
    - Be able to send control signals that change the operation of the ESP32 MCU
    - Store data locally on smartphone to use in analytics at a later time
    - Reliably connect and communicate through bluetooth
    - Automatic tapering algorithm programmed to firmware
    - Safety protocols programmed to MCU

2.4 Tolerance Analysis

The difficulty of the design will lie in the accuracy of delivery of the concentration of a nicotine-like liquid within the device's reservoir. The e-cigarette liquid (e-juice) in commercial e-cigarettes usually lies within a housing that surrounds the heating coil. This design for the housing will have to allow insertion of liquid from another source within the device and not allow liquid to flow backwards, possibly contaminating the dilutant. There could also be an issue with the user inhalation causing unwanted forward flow, disturbing the precision of the mixture in the main reservoir.

Feasibility was analyzed through research of different components involved in the fluid subsystem. This includes micro-pumps, valves, pump drivers, and sensors that rely on controls from the microcontroller and feedback signals that are given to the microcontroller as well. Mainly, the addition of valves between the pump and central chamber will allow us to control the flow of fluids regardless of the inhalation pressure that is posed when the device is being used. To mitigate the risks of backflow and uncommanded forward flow, we have selected micro-peristaltic pumps. The fundamental mechanism of a peristaltic pump involves a rotor compressing a flexible silicone tube against the pump housing. This mechanical compression creates a continuous point of occlusion, effectively acting as a "normally closed" check valve when the motor is stationary.

3. Ethics, Safety, Engineering Standard, and Societal Impact

For this project, nicotine will not be used for this iteration's demonstration, so there is less of a risk toward using it. However, we may choose to work with it at some point in the future, and the safety of using it should be emphasized. Nicotine is a highly addictive, toxic substance that can be fatal if swallowed or in contact with skin. It is very possible that we can work with it in the proper environment with proper PPE. The design involves a heating element at greater than 200℃, and it implements thermal safety protocols aligned with UL 8139 standards for heating element cutoff. The device uses wireless communication, so it must maintain Bluetooth communications with encrypted pairing (Security Mode 1, Level 4) to prevent unauthorized schedule modifications, ensuring data integrity as outlined in the IEEE Code of Ethics (Canon 1) regarding public safety.

This project provides a societal impact through the public health domain, which directly aligns with IEEE Code of Ethics (1.1). Tobacco remains a leading cause of preventable death globally. This design uses a state-of-the-art device paired with a customized tapering algorithm to take away the difficulties of going through withdrawal symptoms. FadeX has the potential to significantly increase the success rate of cessation, reducing the burden of smoking-related illnesses on the healthcare system. Regarding economic benefits, the cost of vaping (or smoking) is high, but the cost of healthcare for smokers is higher. A device that successfully weans a user off nicotine entirely generates a massive long-term economic benefit for the individual and society. Traditional disposable vapes create massive e-waste, sending millions of lithium batteries and plastic to landfills and local streets annually. FadeX is a refillable, reusable device designed for a long lifecycle. Our product would have a positive environmental impact by significantly reducing plastic and battery waste.

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