ECE 445: Senior Design Laboratory

Offline Multi-Factor Authentication Smart Safe

Design Document

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1 Introduction

1.1 Problem Statement

Traditional safes often rely on a single point of failure: a physical key that can be stolen or a numeric password that can be observed. Modern "smart" safes frequently solve this by adding connectivity, yet this introduces significant privacy risks and vulnerability to remote hacking through Wi-Fi or cloud-based vulnerabilities. There is a market gap for a high-security desktop safe that provides multi-factor authentication (MFA) with the convenience of biometrics while remaining entirely offline to ensure data privacy and resistance to network-based attacks.

1.2 Solution Overview & Visual Aid

Our solution is an Offline Multi-Factor Authentication (MFA) Smart Safe. It integrates three independent verification factors: Edge AI facial recognition, fingerprint scanning, and RFID. By utilizing a dual-MCU architecture, the system separates heavy AI processing (ESP32-S3) from critical control logic (STM32). The system remains completely disconnected from any network, processing all biometric data locally on the "edge." The locking mechanism is a 12V electromechanical solenoid controlled by a robust power distribution network.

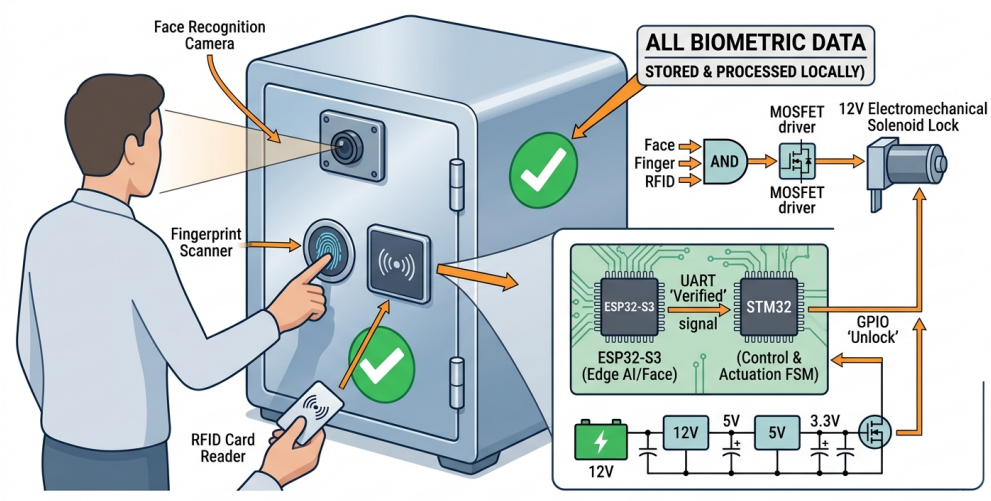

Figure 1: Conceptual Operation of the Offline Multi-Factor Authentication Smart Safe

1.3 High-Level Requirements

1. **Security and Accuracy:** In "High-Security Mode," the system must require all three factors to match. The False Acceptance Rate (FAR) for the combined biometric system must be less than 0.001%.

2. **Latency:** From the moment the final authentication factor is presented, the system must actuate the electromechanical lock within 1.5 seconds.

3. **Power Robustness:** The system must operate on battery power for at least 100 unlock cycles. During the 12V solenoid actuation (peak current), the 3.3V logic rail must not drop by more than 5% (165mV) to prevent MCU brownout.

2 Design

2.1 Block Diagram

The system is divided into three main sub-units: Power, Authentication (Sensors), and Control/Actuation.

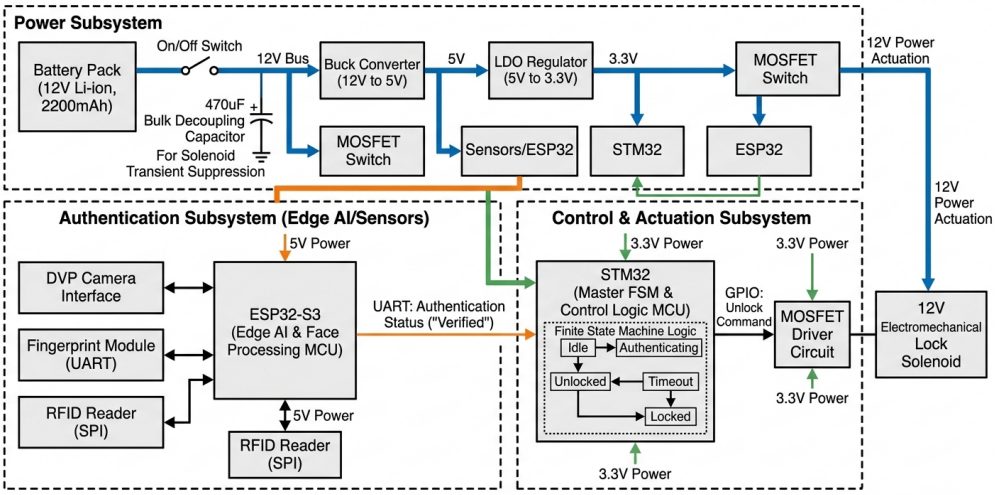

Figure 2: System Block Diagram for the Offline Multi-Factor Authentication Smart Safe

2.2 Subsystem Descriptions

2.2.1 Authentication Subsystem

This subsystem handles all user inputs. The ESP32-S3 interfaces with a DVP camera to perform local face detection using an optimized CNN model. The Fingerprint Module and RFID Reader communicate via UART/SPI. This subsystem is responsible for converting raw biometric data into a "Verified/Not Verified" status.

2.2.2 Control and Actuation Subsystem

The core is an STM32 Microcontroller running a non-blocking Finite State Machine (FSM). It polls the Authentication subsystem and manages the "High-Security" logic. Once the FSM reaches the "Unlock" state, it triggers a high-side MOSFET driver to provide 12V to the electromagnetic lock.

2.2.3 Power Subsystem

This system regulates a 12V Lithium-ion battery pack. It uses a buck converter to provide 5V for the sensors and an LDO for the 3.3V logic rails. It includes heavy decoupling capacitors to handle the transient load of the solenoid.

2.3 Requirements & Verifications

Subsystem Requirement	Verification Procedure	Success Confirmation
Control Subsystem: STM32 must process UART signals from ESP32 and Fingerprint module within 100ms.	Use a Logic Analyzer to measure time between the end of UART transmission and the GPIO trigger to the MOSFET.	Time measured is < 100ms over 10 trials.
Power Subsystem: 3.3V rail must stay within $3.3V \pm 0.165V$ during solenoid activation.	Use an Oscilloscope in "Single Trigger" mode to capture the VCC rail when the 12V lock is fired.	Voltage dip is less than 5% of nominal 3.3V.
Authentication: ESP32-S3 must identify a registered face in under 1.2s.	Use internal timers (millis) to output the duration from frame capture to recognition result over Serial Monitor.	Average time over 20 successful attempts is < 1.2s.

2.4 Tolerance Analysis

A critical challenge in this design is the Power Distribution Network (PDN) stability during the high-current transient caused by the 12V solenoid lock. The solenoid has a DC resistance of approximately $R_L = 10\Omega$.

When the MOSFET switches on:

$$I_{peak} = \frac{V_{bat}}{R_L} = \frac{12V}{10\Omega} = 1.2A \tag{1}$$

This $1.2A$ surge can cause a voltage drop across the battery's internal resistance ($R_i \approx 0.5\Omega$) and the PCB traces. To prevent the STM32 ($V_{min} = 2.0V$) and ESP32 from resetting, the 3.3V LDO requires a minimum input of $3.6V$ (assuming $300mV$ dropout).

We must ensure that:

$$V_{drop} = I_{peak} \times (R_i + R_{trace}) < V_{margin} \tag{2}$$

Assuming $R_{trace} = 0.1\Omega$:

$$V_{drop} = 1.2A \times 0.6\Omega = 0.72V \tag{3}$$

Since $12V - 0.72V = 11.28V$, which is well above the $5V$ buck converter input threshold and the $3.6V$ LDO threshold, the logic remains safe. However, we will implement a $470\mu F$ bulk capacitor near the MOSFET to source the initial surge current $I = C\frac{dv}{dt}$ to further smooth the transition.

3 Cost and Schedule

3.1 Cost Analysis

The cost analysis focuses on the component and fabrication expenses required to build the Offline MFA Smart Safe prototype. All costs are listed in Chinese Yuan (CNY).

3.1.1 Parts Cost

To maintain a budget of approximately ¥1,000 while ensuring high security, we have selected cost-effective yet reliable hardware. The estimated costs for a single prototype are detailed in Table 1 below.

Description	**Manufacturer**	**Quantity**	**Cost (CNY)**
Compact Steel Safe Chassis (Modified)	Generic	1	¥350.00
ESP32-S3-WROOM-1 Module	Espressif	1	¥45.00
STM32F103C8T6 (Blue Pill) MCU	STMicro	2	¥40.00
OV2640 Camera Module (DVP)	Arducam	1	¥35.00
AS608 Optical Fingerprint Sensor	Grow	1	¥85.00
RC522 RFID Reader + 13.56MHz Tags	NXP	1	¥25.00
12V 3000mAh Lithium Battery Pack	Generic	1	¥120.00
12V Electromagnetic Solenoid Lock	Generic	1	¥45.00
Custom PCB Fabrication (2-Layer)	JLCPCB/JLC	2	¥100.00
Power Circuit Components (Buck, LDO, MOSFETs)	Various	1	¥60.00
Enclosure Fittings and Mounting Brackets	Local Hardware	1	¥50.00
Total Parts Cost			**¥955.00**

3.2 Schedule

- **Week 1:** Finalize component selection and order parts.
- **Week 2:** Complete PCB schematic and footprint verification.
- **Week 3:** PCB Layout and submission for fabrication.
- **Week 4:** Develop ESP32-S3 Face Recognition firmware (Edge AI).
- **Week 5:** Develop STM32 FSM logic and peripheral drivers.
- **Week 6:** Assemble PCB and perform Power Subsystem testing.
- **Week 7:** Integrate Sensors with STM32 and debug communication.

- **Week 8:** Final system integration and enclosure mounting.

4 Ethics and Safety

We adhere to the **IEEE Code of Ethics**. A primary concern is biometric privacy. By processing all data offline, we ensure that user facial and fingerprint templates are never exposed to the internet, fulfilling the principle of protecting privacy.

Regarding physical safety, the 12V solenoid can become hot during prolonged activation. Our FSM includes a "Timeout" feature that automatically cuts power to the lock after 5 seconds. Furthermore, a mechanical override key is included to ensure the user can access the safe in the event of total electronic failure or battery depletion.

5 References

1 IEEE, "IEEE Standard for Biometric Open Protocol Standard," IEEE Std 1888.3-2013.

2 STMicroelectronics, "STM32F405xx Datasheet," Rev. 4, 2023.

3 Espressif Systems, "ESP32-S3 Series Datasheet," v1.1, 2022.