ECE 445/ME 470

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Smart Medicine Box

Team #6

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1 Introduction

1.1 Problem Statement

The rapid growth of the global elderly population is intensifying pressure on healthcare systems, particularly in the area of medication adherence. By 2050, the population aged 60 or above is expected to reach nearly 2 billion worldwide, and studies have shown that over 22% of adults aged 40–79 in the United States are engaged in polypharmacy, the simultaneous use of five or more medications [1]. This increases the likelihood of dosing errors, missed medications, and adverse drug events—risks that are especially dangerous for older adults with cognitive decline or limited independence. While existing smart pillboxes provide basic functionalities such as alarms and storage, they still rely heavily on manual pill organization and often suffer from low capacity, poor accuracy in dispensing, or user-unfriendly interfaces [2][3].

1.2 Solution

1.2.1 Overview

To address these limitations, we propose a novel smart medicine box that integrates mechanical automation and multimodal AI assistance to enhance the safety, accuracy, and independence of elderly users in managing their prescriptions. Our design combines an air-pump-based suction mechanism for automatic pill extraction, a rotating multi-compartment storage tray, and a mobile application for remote control, inventory management, and real-time prescription validation via vision-language models. Compared to existing solutions, our system emphasizes precision, modularity, and user convenience. To contextualize our proposed solution, Figure 1 presents a visual overview of the system in use. It illustrates how the smart medicine box interacts with the user and external components, including a mobile application and a cloud-based prescription analysis module. This scenario-based diagram highlights key functionalities such as automatic pill dispensing, remote control via smartphone, and AI-driven prescription verification, demonstrating how our solution fits seamlessly into a typical daily medication routine.

1.2.2 Design Iteration Summary

The smart medicine box has undergone a series of structured design iterations to improve mechanical reliability, dispensing accuracy, and manufacturability. These modifications were informed by experimental testing, user scenario analysis, and fabrication constraints.

The pill-grabbing mechanism was upgraded from a single-axis to a dual-axis motor, improving vertical motion stability and control. The linkage design was simplified to reduce part count and frictional losses. Additionally, four tray geometries—flat-bottom, bowl, pyramid, and conical—were prototyped and tested for suction compatibility. The conical

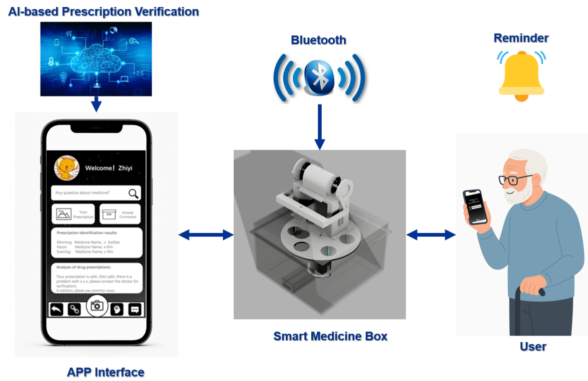


Figure 1: Smart Medicine Box System Interaction Diagram

configuration demonstrated superior performance and was selected for final implementation.

The rotation system was revised with the integration of a stepper motor, enabling precise angular alignment of the pill compartments. The original 12V air pump was replaced with a 24V variant to address insufficient suction force when handling heavier pills. Future revisions will incorporate adjustable pipette dimensions to improve compatibility with varied pill sizes.

The housing design was also optimized for manufacturability. The initial cylindrical 3D-printed structure was replaced with a rectangular enclosure assembled from laser-cut acrylic panels. This change reduced production time and cost while improving structural accessibility and modularity.

These iterative enhancements reflect a design process that prioritizes functional robustness, manufacturability, and long-term scalability.

1.3 High-Level Requirements List

- The system shall be capable of dispensing the correct medication at the correct scheduled time without requiring manual pill handling from the user.
- The mobile application shall allow users or caregivers to input and review prescriptions, and it must wirelessly synchronize data with the smart medicine box in real time.
- The system shall utilize cloud-based AI to analyze prescriptions for safety, dosage accuracy, and potential drug interactions before execution of pill dispensing.
- The smart medicine box shall issue a clear reminder to notify the user when medication is ready to be taken, and log whether the user acknowledged the reminder.

2 Design

2.1 Physical Diagram

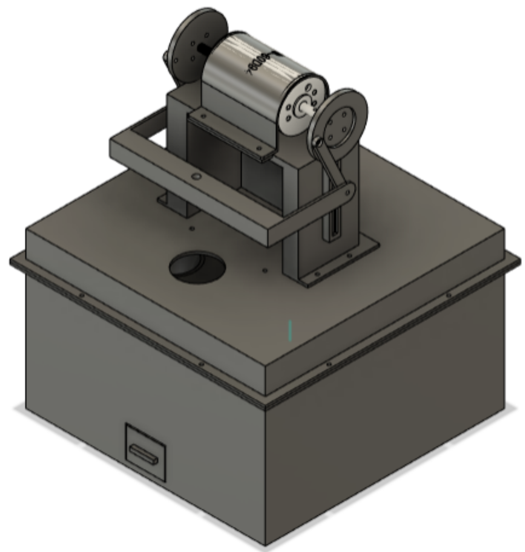


Figure 2: Physical Design of Medicine Box

The mechanical design of this smart medicine box includes a linkage mechanism, air pump grabbing mechanism, rotating medicine storage device, and medicine collecting part. The main working principles are as follows:

(a) Medicine Storage
Inside the medicine box, there are six separate storage compartments, with five used for storing different types of medicine and one compartment designed as a passage for dropping medicine into the collecting part.
The storage device can rotate automatically to position the correct medicine compartment for the air pump mechanism to grab. Once the medicine drops into the passage compartment, it falls into the collecting part at the bottom, making it easy for the patient to retrieve the medicine.

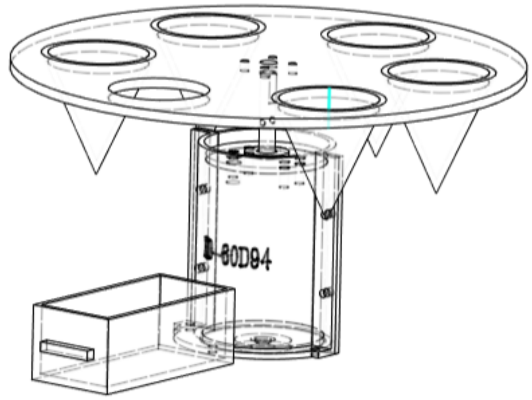


Figure 3: Storage Part of the Box

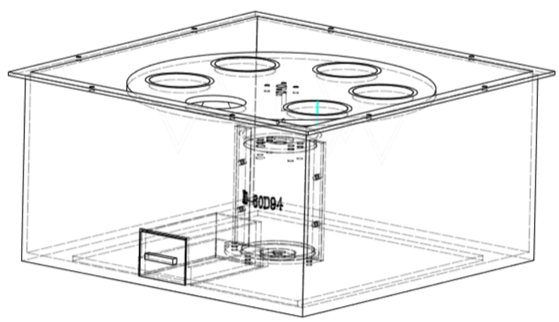


Figure 4: Storage Part with Shell

(b) Medicine Grabbing and Dropping
The linkage mechanism connected to the air pump drives the grabbing device up and down, allowing it to grab the specified medicine and place it into the drop compartment.

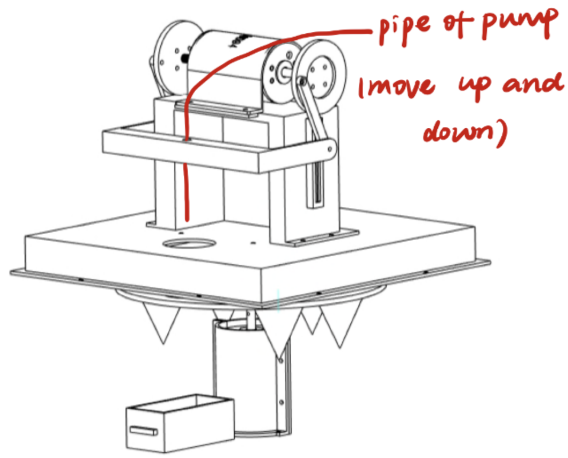


Figure 5: Grabbing Mechanism with Upper Shell

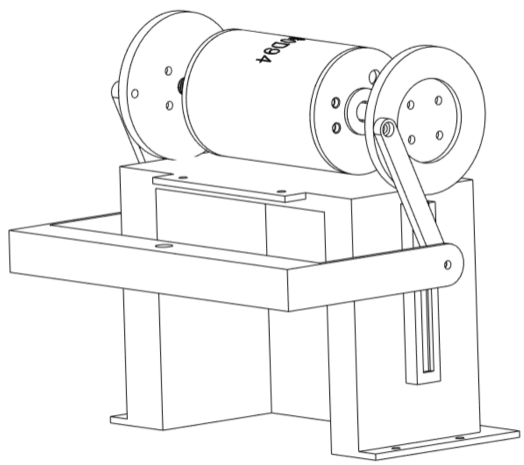


Figure 6: Grabbing Mechanism in Detail

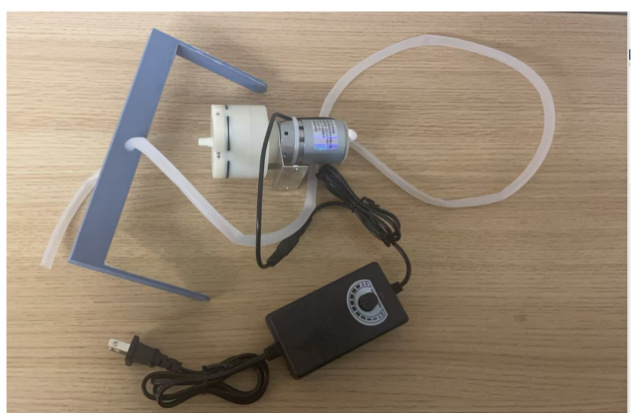


Figure 7: Air Pump

2.2 Block Diagram

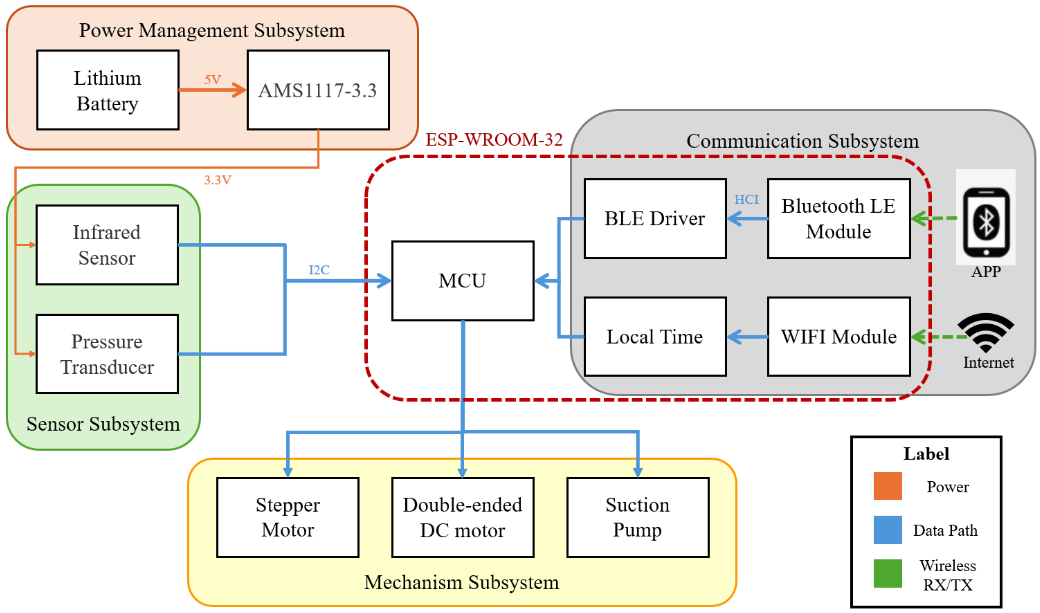
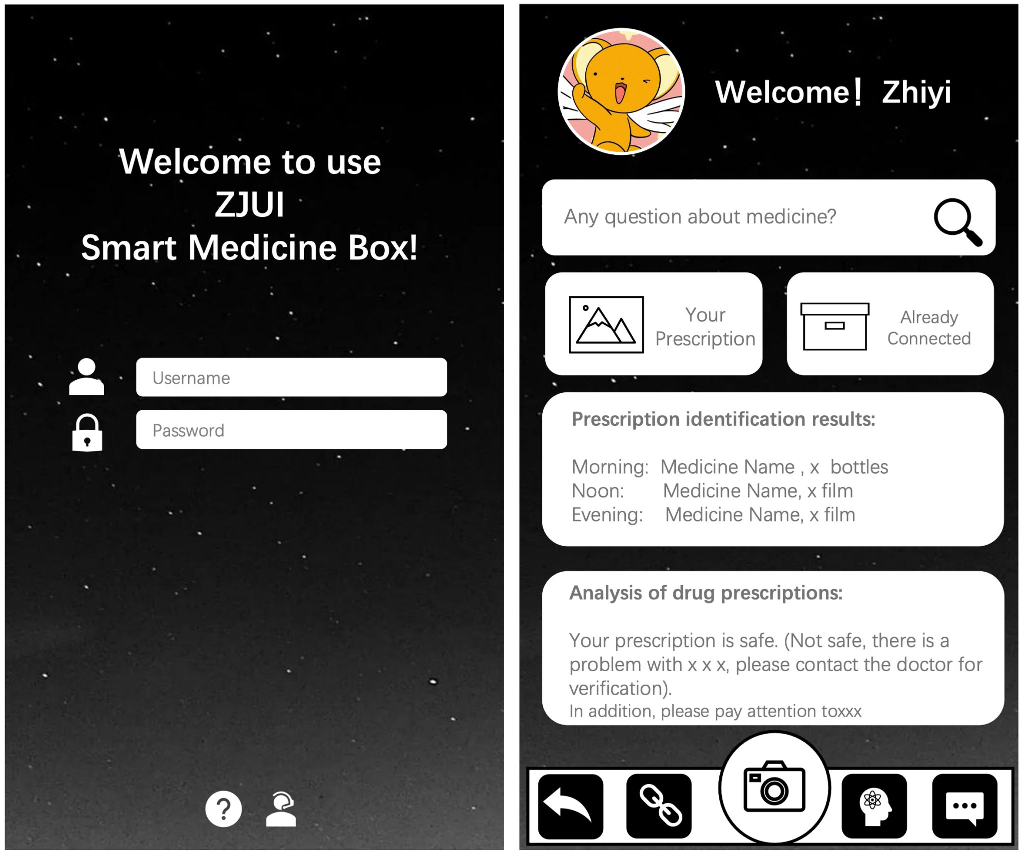


Figure 8: Block Diagram

2.3 Blocks Description

2.3.1 App Subsystem Description

- **Descriptions**
  We will use a mobile app in Figure9 to assist in obtaining prescriptions and transmitting the prescription content to the smart medicine box. The following is an introduction to the process of this app:
  This app provides users with a convenient and intelligent prescription management process. First, users only need to click the photo button on the app interface to easily capture pictures of the prescriptions.
  Then, the app will use the advanced image recognition technology of the multimodal large model through API to accurately identify the pictures taken and to confirm the types and dosages of the prescription drugs.
  After the identification is completed, the app will send the identified prescription drug information again to the large language model for further analysis. This process ensures the accuracy and legality of the prescription, providing users with a safer medication guarantee. During the analysis process, the app will check whether the prescription drugs are safe and make corresponding judgments based on the analysis results. At the same time, the large language model can give patients advice on matters to pay attention to when taking the medicine and health-related suggestions such as diet and exercise based on the prescription.
  If the prescription drugs are safe and correct, the app will proceed to the next step,



(a) APP welcome (b) APP User

Figure 9: App Front Interface

which is to transfer the prescription information to the smart medicine box. The smart medicine box can automatically distribute the corresponding drugs to patients based on the prescription information. After transmitting the prescription information, the medicine box distributes the drugs and ensures that patients can take the required drugs on time and in the correct amount.
In summary, this app combines technologies such as photo recognition, API invocation of the multimodal large model, and Bluetooth transmission to provide users with a comprehensive and intelligent prescription management process. It not only improves the accuracy and safety of medication but also brings users a more convenient and efficient medication experience.

- **Requirements&Verifications**

Requirement	Verification
The app can take photos of the prescription.	Given a prescription, the user can take the photo and see the picture on the App Interface.
For the prescription photos that have been taken, the App can realize the function of calling a large model for identification and analysis.	For the prescription photos that have been taken, the user can see the identification and analysis results on the interface.
The app can connect to the esp32 and pass the output of the large model to the esp32 via Bluetooth.	Esp32 When connected to the app, can get the information from the app.

2.3.2 Power Management Subsystem

- **Description**
  The Power Management Subsystem provides regulated power to all components. It uses a lithium battery as the primary source, which is stepped down to 5V and further regulated to 3.3V via the AMS1117-3.3 LDO. This subsystem connects to every other subsystem (e.g., Communication, Sensor, Mechanism) by supplying stable voltage rails.

- **Components**
  - **Lithium Battery**
    - **Function**: Primary power source (3.7V nominal, 2.5V–4.2V range).
    - **Requirements**:
      - Must deliver $\geq$ 2A peak current.
      - Requires protection circuit to prevent over-discharge (< 2.5V).
  - **5V Rail**
    - **Function**: Distributes 5V power to high-current components.
    - **Requirements**:
      - Voltage stability: $5\text{V} \pm 0.1\text{V}$ under 1A load.
  - **AMS1117-3.3**
    - **Function**: Regulates 5V to 3.3V for low-voltage components.
    - **Requirements**:
      - Output current ≥ 800mA.
      - Thermal derating $< 20\%$ at full load.

- **Requirement&Verification**

Requirement	**Verification**
A $3.3\text{V} \pm 0.1\text{V}$ power is provided to the STM32. Noise should be $\leq 50\text{mV}$.	Use the oscilloscope to test the STM32 power voltage from the power management subsystem. The result should be a voltage of $3.3\text{V} \pm 0.1\text{V}$ with noise should be $\leq 50\text{mV}$.
A $12\text{V} \pm 0.5\%$ power is provided to the step model and double-ended motor. The maximum current should be 10A.	Use the oscilloscope to test the step model and double-ended motor power voltage from the power management subsystem. The result should be a voltage of $12\text{V}\pm0.5\%$ with maximum current 10A.
A $24\text{V}\pm3\%$ power is provided to the suction engine with a maximum current 8A.	Use the oscilloscope to test suction engine power voltage from the power management subsystem. The result should be a voltage of $24\text{V} \pm 3\%$ with maximum current 8A.

2.3.3 Communication Subsystem

- **Description**
  This subsystem handles the data exchange with the App and the Internet. The ESP-WROOM-32 MCU acts as the central hub, interfacing with the Bluetooth LE Module (via HCI) for BLE communication to the APP and the Wi-Fi Module for internet connectivity. It connects to the MCU in the ESP-WROOM-32.

- **Components**
  - **ESP-WROOM-32 (MCU)**
    * **Function**: Central processing unit for data handling and protocol management.
    * **Requirements**:
      · Must support dual-core operation for real-time task scheduling.
      · GPIO pins must tolerate 5V logic for motor control.
  - **BLE Driver (HCI)**
    * **Function**: Manages Bluetooth Low Energy
    * **Requirements**:

    - RSSI > -80dBm for stable connection.
    - Latency < 50ms for command transmission.
- **Wi-Fi Module**
  - **Function**: Connects to the internet for data upload (e.g., sensor logs).
  - **Requirements**:
    - IEEE 802.11 b/g/n compliance.
    - Minimum throughput: 1Mbps.

- **Requirement&Verification**

Requirement	**Verification**
The bluetooth of the STM32 can successfully connect to the APP with a connection time ≤ 5s and maximum working distance ≥ 10m. Packet loss rate should be $\leq 0.1\%$.	Connect the APP to our smart medicine box and measure the connection time. Repeat for some times and the average time should be ≤ 5s. Send 100 instructions to medicine box within a distance of 10m. Caculate the packet loss rate and it should be $\leq 0.1\%$.
The WIFI module should have the ability to connect to the WIFI signal when the RSSI ≥ -70dBm.	Try to connect the STM32 to WIFI signal with -90dBm $\leq$ RSSI ≤ -60dBm and test its success rate.
The STM32 should get a time $\leq \pm 1$sec within the local time so that we can remind users to take pills at accurate time.	Connect the STM32 to the WIFI and then calibrate the module time by NTP. Measure the difference between the module time and standard local time. The difference should be within ± 1sec.

2.3.4 Sensor Subsystem

- **Description**
  This subsystem collects mechanical status data via Pressure Transducer and Infrared Sensor, which is important for MCU to control the Mechanism subsystem and make sure it work as our wanted. The Data collected by this subsystem is sent to the ESP32 via I2C or GPIOs.

- **Components**
  - **Pressure Transducer**
    - **Function**: Measures environmental pressure (0–100kPa).
    - **Requirements**:

        · Accuracy $\pm 0.5\%$ FS.
        · Operating voltage: 3.3V $\pm$ 5%.
  - **Infrared Sensor**
    * **Function**: Infrared Sensor TCRT5000 is used to detect if a tablet is dropped into the collection compartment.
    * **Requirements**:
        · Response time < 1ms.
        · Working circumstances < 500lux.

- **Requirement&Verification**

Requirement	Verification
By editing the parameters in the STM32, the pressure transducer should successfully report the suction action at an accuracy greater than 80%	Open the suction pump and connect the pressure transducer to the air-out. Connect the output of the pressure transducer to the STM32, and then the output of STM32 to a LED test circuit. Try to suck one pill onto the straw. The LED should be light on with a probability of 80% .
After programs compiling, the Infrared sensor should have the ability to report the tablet drop at a accuracy greater than 80%	After installation, try to drop pills into the collection compartment at the same height as the straw does. Connect STM32 processed version of the sensor output to the oscillator, then observe and count its success rate.

2.3.5 Mechanism Subsystem

- **Overview**
This subsystem executes physical actions of the medicine box through a Rotating Engine (motor), a Electrical-Controlled Lock, and a Grabbing Engine. It receives control signals from the ESP32 (via GPIO/PWM) and is powered by the 5V rail. Feedback from sensors (e.g., angular position) ensures precise operation.

- **Components**
  - **Step Motor**
    * **Function**: Drives the rotation of the medicine storage system. Make sure the storage system can stop at any specific storage compartments.

* **Requirements**:
  * Stall current ≤ 1.2A at 5V.
  * Back-EMF protection required.

- **Suction Pump**
  * **Function**: Performs medicine grab and drop through suction.
  * **Requirements**:
    * Pressure feedback accuracy $\pm 5\%$.
    * Operating voltage: 24V $\pm$ 3%V.

- **Double-ended DC Model**
  * **Function**: Drive the suction mechanism. Let the straw move up and down following our requirement.
  * **Requirements**:
    * Operating voltage: 12V $\pm$ 3%V.

- **Requirements&Verifications**

Requirement	**Verification**
Rotate the storage in specific angle.	Use STM32 to specify a rotation Angle between 0 and 360, the system can be rotated to and error in 5 degrees.
The suction mechanism must successfully grab pills weighing $\geq$ 0.2g with a success rate of at least 60% across 20 trials.	Conduct 20 consecutive trials using pills ($\geq$ 0.2g each). Log the number of successful grabs. A successful grab means the pill is fully lifted and transferred to the output compartment. Success rate = (successful trials ÷ total trials) × 100%.
The system must be able to dispense exactly one pill per activation cycle, with an accuracy of at least 60%.	Trigger 20 grab cycles, each intended to dispense a single pill. Use an optical or weight sensor to count the number of pills actually dispensed each time. The system should dispense exactly one pill in at least 12 out of 20 trials. Record results in a table.

2.4 System Working Flow Chart

2.4.1 Overall Workflow

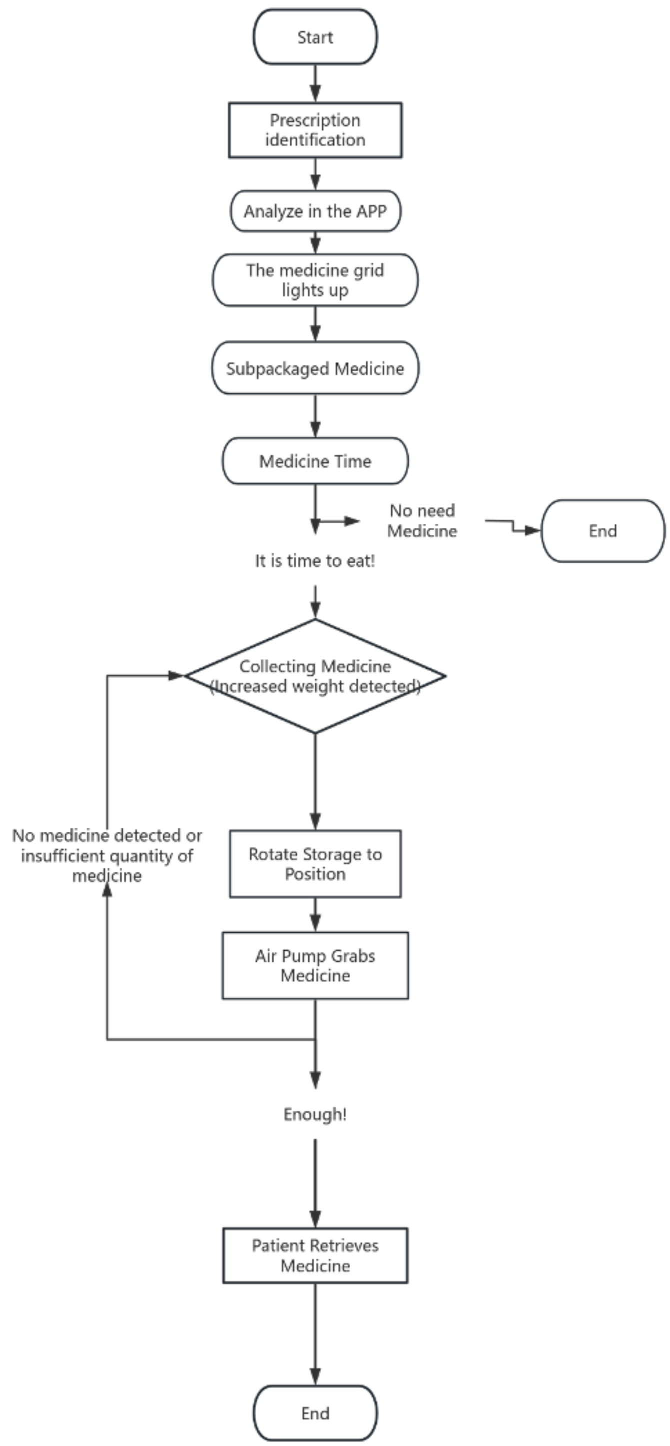


Figure 10: Smart Medicine Box Workflow

2.4.2 App Workflow

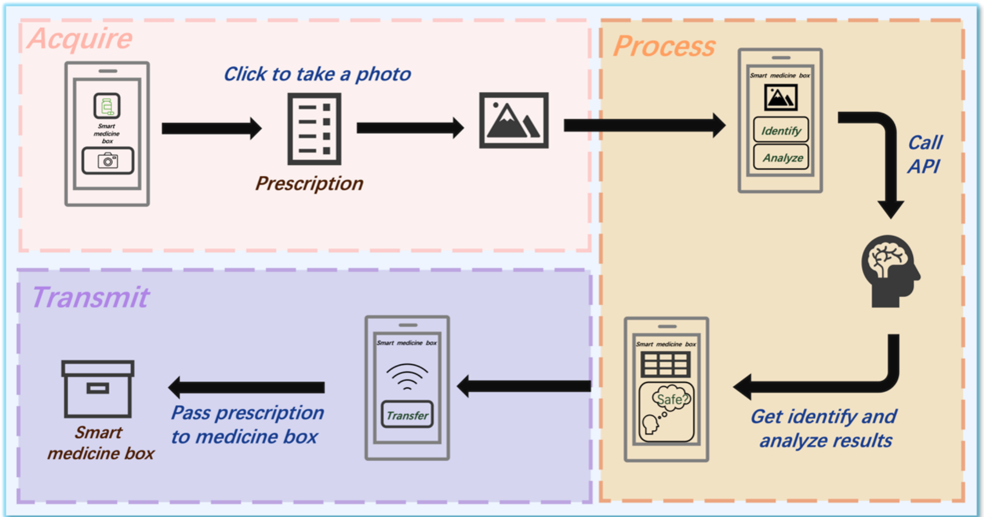


Figure 11: App workflow

2.5 Risk Analysis

2.5.1 App Making

When confronted with the task of making an app to do prescription recognition and analysis, we are faced with two core challenges. The following is a detailed elaboration and supplementation of these difficulties:

Risk One: Select an appropriate multimodal large model to accurately perform prescription recognition and analysis.
Prescription recognition and analysis is a complex and meticulous process, which requires the selected multimodal large model to not only possess strong image recognition capabilities (to parse the text, symbols, and graphic information on the prescription) but also have natural language processing (NLP) technology to understand and analyze the semantic content of the prescription. Currently, there are numerous models on the market, each excelling in different fields and application scenarios. How to select a multimodal model that can not only efficiently handle image data but also deeply understand textual information has become an urgent problem to be solved. Additionally, the model's accuracy, generalization ability, and processing speed are also key factors in evaluating its applicability.

Risk Two: Building an efficient and precise prompt to guide the model to output the expected recognition and analysis results and format.
When using multimodal large models for prescription analysis, how to construct a prompt word to do analysis and ensure the output meets specific requirements is another major challenge. This requires the prompt not only to accurately reflect the core tasks of pre-

scription recognition, such as identifying drug names, dosages, and usage methods but also to consider the format requirements of the output to ensure that the results can be directly applied to the processing of medicine boxes.

2.5.2 System Construction

Identified Risk: Thermal Management of AMS1117-3.3 LDO
The AMS1117-3.3 linear regulator is critical for providing stable $3.3\,\mathrm{V}$ power to the MCU, sensors, and wireless modules. However, its thermal performance poses a significant risk due to high power dissipation under load.

Risk Justification

- **High Power Dissipation**:

$$\begin{aligned} P_{\text{dissipated}} &= (V_{\text{in}} - V_{\text{out}}) \times I_{\text{load}} \\ &= (5\,\mathrm{V} - 3.3\,\mathrm{V}) \times 0.8\,\mathrm{A} \\ &= 1.36\,\mathrm{W} \end{aligned}$$

- **Thermal Analysis**:

$$\begin{aligned} \Delta T &= P_{\text{dissipated}} \times R_{\theta(\text{JA})} \\ &= 1.36\,\mathrm{W} \times 90\,^{\circ}\mathrm{C/W} \\ &= 122.4\,^{\circ}\mathrm{C} \end{aligned}$$

  Junction temperature at $25\,^{\circ}\mathrm{C}$ ambient:

$$T_j = 25\,^{\circ}\mathrm{C} + 122.4\,^{\circ}\mathrm{C} = 147.4\,^{\circ}\mathrm{C} \text{ (Exceeds } 125\,^{\circ}\mathrm{C} \text{ limit)}$$

Acceptable Tolerances

Table 1: Tolerance Requirements

Parameter	Value
Maximum junction temperature	$125\,^{\circ}\mathrm{C}$
Maximum allowable power dissipation	$1.11\,\mathrm{W}$
Maximum safe load current	$0.65\,\mathrm{A}$

Mitigation Strategies

1. **Switch to Buck Converter**:

$$P_{\text{dissipated}} = P_{\text{in}} \times (1 - \eta) = (5\,\mathrm{V} \times 0.8\,\mathrm{A}) \times 0.1 = 0.4\,\mathrm{W}$$

2. **Add Heatsink**:

$$\begin{aligned} R_{\theta(\text{total})} &= R_{\theta(\text{JA})} + R_{\theta(\text{heatsink})} \\ &= 90\,^{\circ}\text{C/W} + 20\,^{\circ}\text{C/W} \\ &= 110\,^{\circ}\text{C/W} \end{aligned}$$

3. **Load Current Reduction**:

$$I_{\text{max}} = \frac{P_{\text{max}}}{V_{\text{in}} - V_{\text{out}}} = \frac{1.11\,\text{W}}{1.7\,\text{V}} = 0.65\,\text{A}$$

Conclusion
To meet high-level requirements:

- Replace LDO with switching regulator (e.g., MP1584)
- If retaining LDO:
  - Limit load current to $0.65\,\text{A}$
  - Add heatsink with $R_\theta \leq 20\,^{\circ}\text{C/W}$

2.5.3 Smart Box Construction

The interface between the air pump grabbing mechanism and the rotating medicine storage system poses the greatest difficulty in implementation due to the following reasons:

- **High Precision Requirements:** The air pump must accurately grab the correct medicine, or it may result in incorrect dispensing.
- **Synchronization of Rotation and Grabbing:** The rotation of the storage system must be precisely aligned with the air pump's grabbing motion to prevent misalignment.
- **Compatibility with Different Medicine Sizes:** The air pump needs to accommodate variations in medicine size and shape to ensure successful gripping.

To ensure functionality, the following tolerances should be maintained:

- **Rotation Positioning Error:** ±1° (Ensuring that the medicine compartment aligns with the grabbing position).
- **Air Pump Grabbing Position Error:** ±0.5 mm (To ensure stable gripping of the medicine).
- **Air Pump Force Control:** The suction power should be adjustable based on the weight and fragility of the medicine to prevent damage or failed grabs.

3 Costs

Our fixed development costs are estimated to be 100¥/h, 10 hours/week for four people. We consider the approximate cost of our final design this semester (16 weeks), neglecting the central server, mesh network optimization, and partnerships with NGOs:

$$100/h \cdot people \times 10h/week \times 16weeks \times 4people = 64000$$

Our parts and manufacturing prototype costs are estimated at 202.5¥ each:

Part	**Cost**(¥)/one	**Number**	**Cost(¥)**
Air pump(24V)	44.86	1	44.86
Relay module	3.62	2	7.24
Air pump(12V)	39.86	1	39.86
Two-axis motor	60.47	1	60.47
Sensor	170	1	170
Stepper motor	40	1	40
API	50	1	50
TOTAL			202.43

So,
Since we will only build one smart medicine box, this yields a total development cost of 64202.43¥.

4 Schedule

Week	Ruolin&Wentao	Yutong	Zhiyi
4/14/25	Revise the design based on updated Parts. Choose proper sensor.	Complete the motion control for the double-ended engine to perform the medicine suction. Together with the suction sensor, realize the stop and motion part of the suction mechanism.	Complete the software front-end design and realize the page jump function.
4/21/25	Continue 3D printing for delicate parts. Make the shell with acrylic.	Complete the rotation control mechanism. Make sure a specific rotation based on time and prescription.	App connection API to perform picture analysis and prescription safety analysis. Realize Bluetooth transmission between app and esp32, and send prescription content to esp32.
4/28/25	Assemble and test. Help with control section.	Integrate the power transformer circuit.	Improve all the functions of the App, and use it in combination with the medicine box for testing.
5/5/25	Improve based on tests.	Integrate and refine the prototype.	Improve and modify the App according to the combined use with the medicine cabinet.
5/12/25	Prepare for Mock Demo	Prepare for Mock Demo	Prepare for Mock Demo
5/19/25	Prepare for Final Demo and Video	Prepare for Final Demo and Video	Prepare for Final Demo and Video
5/26/25	Prepare for Final Presentation and Report	Prepare for Final Presentation and Report	Prepare for Final Presentation and Report

5 Ethic and Safety

5.1 Ethics

The smart medicine box handles sensitive medical information and directly impacts patient health, so ethical considerations are crucial.

- **Privacy and Data Security**: The system must ensure that prescription data is securely stored and transmitted to prevent unauthorized access. Encryption and strict access control should be implemented.
- **Accuracy and Reliability**: Prescription recognition and medication dispensing must be highly accurate to avoid errors that could lead to incorrect dosages or missed medications. A manual verification step can be integrated to enhance safety.
- **User Trust and Transparency**: Patients and caregivers must be fully informed about how the system works and its limitations. Clear instructions and feedback mechanisms should be provided to users.

Since this project does not involve direct human or animal testing, IRB or IACUC approval is not required. However, ethical best practices must still be followed in handling prescription data and ensuring patient safety.

5.2 Safety

The smart medicine box includes several mechanical and electrical components, requiring safety measures in both design and operation.

- **Electrical Safety**: All wiring and power connections must be insulated properly to prevent short circuits and electrical hazards. The system should be designed to shut down safely in case of power failure.
- **Mechanical Safety**: The rotating storage and air pump mechanisms should be designed with proper tolerances to prevent jamming or accidental medication spillage. Safety guards may be added where necessary.
- **End-User Safety**: The device should be user-friendly to prevent misoperation. If a malfunction occurs, the system should provide an alert rather than dispensing incorrect medication.
- **Compliance with Safety Standards**: The design should follow medical device safety guidelines to ensure reliability and minimize risks.

If hazardous materials or high-voltage components are introduced in future iterations, proper safety training and documentation (such as a Lab Safety Manual) will be required.

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