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Development of a Smart Cabinet Lock Based on Finger Vein Technology

Fan Zhang*

Capital Normal University High School, Beijing 100048, China

***Corresponding author:** Fan Zhang, szzhangfan2023@163.com

Abstract: In response to the requirements for the security and recognition accuracy of cabinet locks in communications, electric power, energy, chemical, IDC computer rooms, daily homes, and other occasions, a smart cabinet lock with multiple door-opening methods based on finger vein biometric technology is developed. The main method to unlock the cabinet is via finger vein unlocking; that is, the identification and verification of information by analyzing the pattern of the veins on the finger, and the achievement of identity verification and identification through biological detection. At the same time, it supports IC or ID card unlocking and mechanical manual unlocking. In order to simplify the overall structure, the internal mechanical structures of the aforementioned three unlocking methods are simplified into one. Its design focuses on the hybrid mechanical transmission structure and the finger vein module as well as utilizes the functions of each module. The principle is divided into blocks. Through processing and purchasing, the smart cabinet lock device is assembled, and its initial functional requirements are tested with physical objects. From the test results, it can be appreciated that the structural size, unlocking method, and two-way unlocking function of the smart cabinet lock meet the requirements, and its recognition accuracy is high, with good security and certain practical application prospects.

Keywords: Finger vein technology; Smart cabinet lock device; IC/ID card read-write head; Hybrid mechanical design; Multiple unlocking methods

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1. Background

With the improvement of people's living standards and the emphasis on safety, as well as the maturity and development of smart homes, biotechnology, and the Internet of Things, the development of smart locks is relatively rapid. Its foreign research and development is relatively early, and the technology is relatively mature. For example, the United States and Europe have relatively complete and strict standards; smart locks have uniform sizes, lock cylinders, lock bodies, etc. have related regulations, and the smart locks currently used are mainly simple types.

The smart locks in Japan and South Korea are relatively mature in terms of industry precipitation, development patterns, and market penetration. Their penetration rates are relatively high. The overall penetration rate of China's smart lock market is low, but it has entered a stage of rapid development in 2016. In recent years, under the support of government policies, the rapid development of artificial intelligence, and the surge of consumer demand in the field of smart homes, China's smart home industry is developing and penetrating rapidly. In terms of smart home products, most consumers are interested in smart surveillance products, followed by personal care, and surveillance management equipment. As an entry-level product of smart homes and the core product of smart home security products, smart locks have become an indispensable core component of the smart home ecological chain. The smart lock industry has formed a mature industrial cluster composed of accessory suppliers, technical support providers, component suppliers, solution providers, foundries, smart lock manufacturers, distributors, as well as other upstream and downstream companies. The industrial cluster, with smart lock manufacturers as the core, is still expanding, including security companies, electronic communication companies, cloud platform companies, and other companies, bringing in new smart lock application technologies and solutions. The smart lock industry has played an important supplementary role and also promoted the rapid development of the entire industry.

In 2016, China's smart lock retail market officially broke out, which in turn drove the Chinese smart lock market into a period of rapid development. The overall sales volume of China's smart lock industry exceeded 3.5 million sets in 2016. It was estimated that by 2021, the sales of smart door locks in China will exceed 32 million sets. It can be seen that smart locks have a broad market in China.

Similarly, smart cabinet locks are not emphasized enough in industrial places, such as energy, chemical industry, and electric power. In addition, their development is relatively slow, and traditional mechanical opening methods are still the main methods. Traditional mechanical methods have problems with keys as they are easy to lose, easy to forget, and easily copied, resulting in safety issues. Therefore, it is of great significance to develop smart cabinet locks with higher security and recognition accuracy.

Most smart locks in China use multiple identification methods, such as passwords, fingerprints, and mobile phones. Among them, semiconductor fingerprint recognition and optical fingerprint recognition are currently the most mainstream fingerprint recognition technologies in the smart lock industry. With the increasing maturity and development of smart lock-related technologies, face recognition, fingerprint recognition, language recognition, iris recognition, mobile phone unlocking, IoT technology, vein recognition, etc. have been introduced one after another, and the functions as well as applications of smart lock products in the country will be more abundant and diversified. Most of the aforementioned recognition methods of smart locks are based on biological characteristics, such as fingerprints, faces, language, iris, and so on. However, the existing biometrics still have problems, such as being copied, imitated, stolen, and lack of feature stability. For example, the fingerprint recognition technology most used in home smart locks has an error rate of about 4%, and it is easy to be stolen and imitated [1]. However, with the continuous innovation and development of biometrics in terms of basic theories, algorithm models, as well as software and hardware support, there has been a gradual transformation from the first-generation traditional biological characteristics to the second-generation living biological characteristics [2]. Among them, the finger vein feature is now widely used due to its obvious advantages. Compared with other human features such as the face, fingerprint, iris, language, etc., it several characteristics which are advantageous [3].

(1) Stability.
Finger veins are one of the most stable biological characteristics of the human body. The distribution characteristics of a person's finger veins remain unchanged for life after adulthood.

(2) Unique.
The chance that two people have the same finger vein structure is one in 3.4 billion. Even identical twins with the same DNA have different finger vein morphologies.

(3) Difficult to obtain.
Finger veins are distributed under the skin and have intricate shapes that are difficult to imitate. Finger vein recognition is based on the fact that the heme in the living finger can absorb near-infrared light to form a vein image.

(4) It must be obtained in vivo.
If the finger is detached from the human body, the blood characteristics in the veins will change, making it impossible to obtain an image of the vein and pass the verification of the vein recognition device.

Compared with face recognition and fingerprint recognition, finger vein recognition has the characteristics of living body recognition, non-replicable characteristics of the body, stability, and undecipherable characteristics. It is the safest and most accurate biometric technology in this artificial intelligence era [4]. The comparison of the above-mentioned human biometrics is shown in **Table 1** [5].

Table 1. Comparison of biometrics

Biometrics	Anti-counterfeiting rate	Accuracy	Volume
Fingerprint	Ordinary	Ordinary	Small
Iris	High	High	Big
Face	Ordinary	Low	Big
Palm vein	High	High	Ordinary
Finger vein	High	High	Small

Therefore, an industrial smart cabinet lock based on the finger vein recognition module, with integrated transmission system and hardware system, is designed in this study. The finger vein cabinet lock developed in this study has high recognition accuracy, and the misrecognition rate can be reduced to one in a million; at the same time, it has fast response and can realize rapid recognition in 0.5 seconds; it has wide adaptability and can adapt to various complex and harsh environments. It is compatible with most cabinet doors in the market and supports the installation of sky and earth poles. It adopts a modular structure design, which is convenient for installation and maintenance.

2. Overview

2.1. Objective

The main goal of the project in this study is to complete the design of a smart cabinet lock equipped with the finger vein recognition module. The specific goals of the project are discussed below.

2.1.1. Realize the integration of the finger vein module

Using an integrated finger vein recognition module, the core function of the finger vein cabinet lock can be realized – identifying and judging the finger vein characteristics of the person to be authenticated. If it is an authorized person, it will automatically unlock, otherwise an error will be reported.

2.1.2. Realize the integration of IC/ID card read-write head and emergency mechanical lock

The smart cabinet lock in this study integrates multiple unlocking methods: first, it realizes finger vein unlocking, and at the same time, considering that there may be temporary personnel access, the smart cabinet lock is equipped with IC/ID card read-write head to ensure that these temporary personnel would be able to obtain permission. In addition, it is equipped with an emergency mechanical lock to deal with emergencies, such as power failure and damage to the internal chip of the cabinet lock. The separation of various unlocking methods will complicate the structure; therefore, the integrated design of finger vein unlocking, IC/ID card read-write head, and emergency mechanical lock must be realized.

2.1.3. Realize the function of different unlocking directions

Considering that the actual scenario requires the cabinet door to open to the left and right, the passive gear installation hole of the smart cabinet lock is designed with a double-hole structure, so that the same cabinet lock can achieve the functional requirements of different unlocking directions.

2.2. Key requirements

In the development process, there are some important points to pay attention to. The key requirements for the structure and function of the smart cabinet lock is summarized as follows:

(1) design a smart cabinet lock based on finger vein recognition technology that can directly replace the original mechanical lock, without changing the installation hole of the original mechanical linkage lock, which is convenient and quick to apply;

(2) with a relatively small volume limit, the smart cabinet lock can be applied to both the left-open and right-open modes of the cabinet door to realize a two-way door opening function;

(3) under the relatively small size limit, there are three methods to unlock, including integrated finger vein verification opening, IC/ID card verification opening, and emergency mechanical key opening.

2.3. Technical route

In order to complete the R&D and design of the cabinet lock based on finger vein recognition technology, according to the objectives and key requirements of the project, the technical route of the R&D and design can be determined.

(1) In order to realize the finger vein recognition function, the existing integrated finger vein module E310 is used.

(2) Adopt the IC/ID card read-write head.

(3) The emergency mechanical lock adopts a cylindrical lock.

(4) The electronically controlled opening adopts a miniature geared motor as the executive part.

(5) The structural size of the lock body is restricted by the width and height of the finger vein module and the door opening. The width of the smart cabinet lock is greater than 36 mm. Therefore, the installation hole and the center line of the smart cabinet lock cannot be on the same axis. In order to solve this problem, a gear transmission-transition structure is adopted between the handle transmission shaft and the rack transmission mechanism. The mounting hole of the driven gear adopts a double-hole structure to meet the requirements of the door-opening direction, as shown in **Figure 1**.

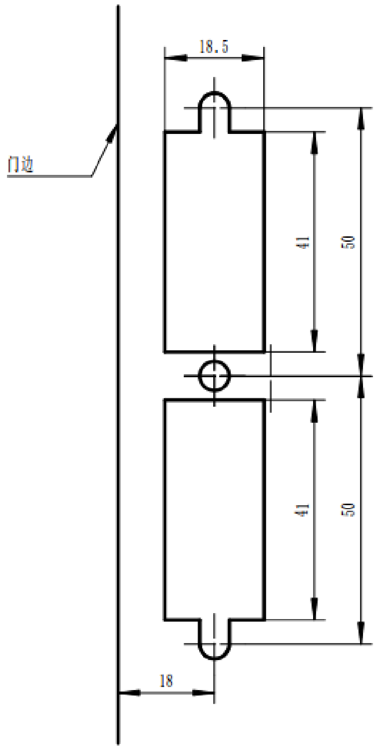


Figure 1. The gear mounting hole structure

3. Overall structure design

The overall structure of the multifunctional cabinet lock based on finger vein recognition technology includes the integrated finger vein module E310, IC/ID card read-write head, emergency mechanical lock, integrated transmission device, geared motor, etc., according to the internal part structure and hardware installation to confirm the overall structure size.

3.1. Confirmation of unlock plan

The existing unlocking methods include IC/ID card unlocking, finger vein unlocking, and mechanical key unlocking. They are independent methods, and each unlocking method has its own specific method.

(1) IC/ID card identification and unlocking.
In regard to IC/ID card identification and unlocking, the user places their IC or ID card close to the IC/ID card reader; then, identification and verification are performed through the IC/ID card reader. If the verification passes, the main control module receives the verification pass signal and controls the information feedback module to send out a prompt sound of verification success. At the same time, the driving mechanism drives the eccentric wheel to push the sliding mechanism upward. The photoelectric detection switch senses and sends a verification success signal to the lock body module. The motor lock is then energized and unlocked. If the verification fails, the main control module receives the verification failure signal and controls the information feedback module to issue a verification failure prompt sound.

(2) Finger vein unlocking.
In regard to finger vein recognition and unlocking, the user places the registered finger vein into the finger vein module for finger vein pattern detection. After the finger vein module undergoes image processing, the detected image is compared with the image in the database. If there are similar samples, the comparison passes. The main control module then receives the comparison pass signal

and controls the information feedback module to send a prompt sound of verification success. At the same time, it sends a signal to the lock body module to open the lock body, and the drive mechanism drives the eccentric wheel to push the sliding mechanism to release the lock handle. Subsequently, the lock handle is rotated to the left or right by the user to unlock. If the comparison fails, the main control module receives the verification failure signal and controls the information feedback module to emit a verification failure prompt.

(3) Mechanical key unlocking.
Mechanical key unlocking is a traditional method, where the user inserts a matching mechanical key into the mechanical lock module to rotate. The lock tongue pushes the sliding mechanism to release the lock handle, and the user can then rotate the lock handle to the left or right to unlock.

When the above three unlocking methods are used alone, the internal unlocking structure is relatively simple. However, in order to achieve multi-threaded unlocking, the internal structure will become complicated, the service life will be shortened, frequent maintenance will be required, and the internal space occupied will be large. Therefore, a new simplified way is needed to merge the above unlocking methods.

3.2. Improvement

In order to realize multiple unlocking methods, this study combines three different unlocking methods by simplifying and integrating. All three signal sources are converted to the motor, the main control module controlling the motor, and finally a single signal output. The research direction of the structural design is as such: a transmission device is pushed through the motor; the transmission device pushes the buckle to eject the handle; the handle then rotates to open the lock module at the rear.

3.2.1. Design idea

According to the spring buckle structure of the spring-loaded ballpoint pen, every time it is pressed, the cylinder in the center will be stuck along the slot. It is then pressed again to use the bottom spring to bounce the cylinder to the next layer of the slot, and finally raising the core. The design idea is shown in **Figure 2**.

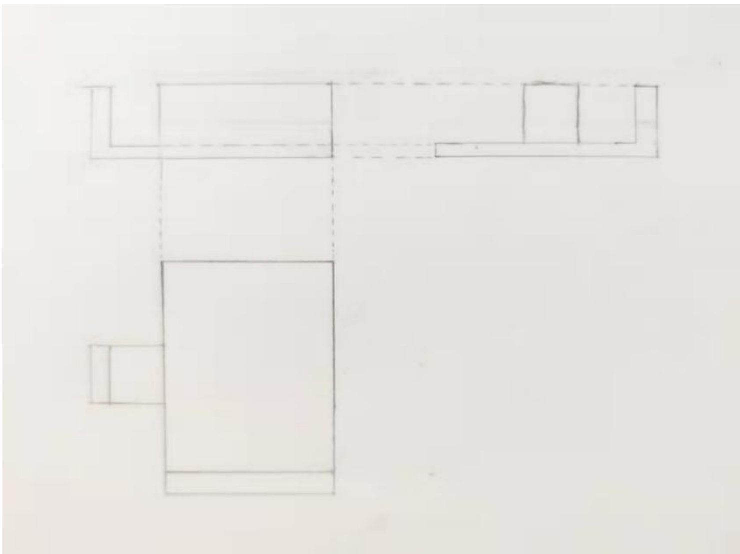


Figure 2. Design sketch 1

The left protrusion is buckled with the motor eccentric wheel. If the finger vein module and the IC/ID card pass the verification, the main control module sends a signal to the motor, and the eccentric wheel rotates to push up the device to open the buckle on the back and the handle pops out.

3.2.2. Changes and adjustments

The first one under the two protrusions on the left is buckled with the motor eccentric wheel. If the finger vein module and IC/ID card are verified, the main control module sends a signal to the motor, and the eccentric wheel rotates to push up the device to open the buckle behind it. In that way, the handle pops out. The protrusion on the left side is connected to the photoelectric sensor switch to ensure that the eccentric wheel rotates and pushes the device to a certain height, not too low or too high. The upper protruding buckle is equipped with a spring, so that it does not only rely on gravity to return to position. The modifications and adjustments are shown in **Figure 3**.

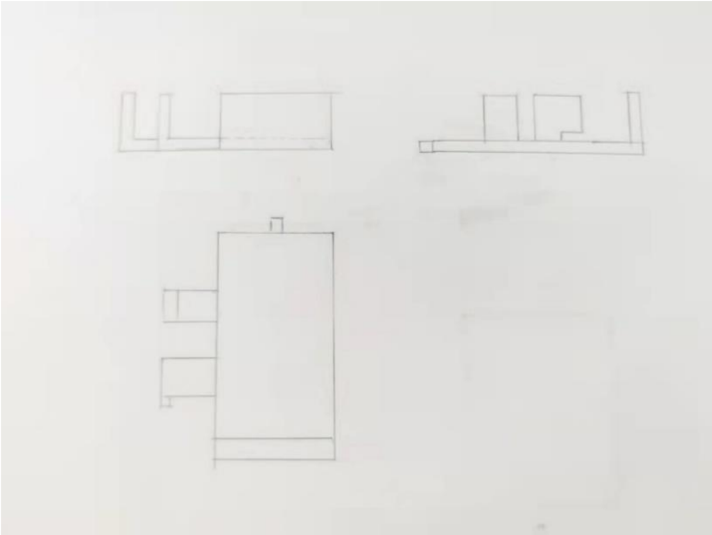


Figure 3. Design sketch 2

3.3. Mechanical transmission

3.3.1. Principles of mechanical transmission

The above combines and optimizes the unlocking method of the multifunctional cabinet. The transmission device between the unlocking gears is determined. There are three unlocking methods for the multifunctional cabinet lock. Among them, the transmission process of IC card unlocking is the same as that of finger vein unlocking, whereas the transmission process of mechanical key unlocking is purely manual unlocking. **Figure 4** is a flow chart and mechanical coordination diagram of the two transmission processes of the smart cabinet lock designed in this study.

The transmission principle of the multifunctional cabinet lock is as such: after passing the verification, the motor receives a signal and starts to rotate, driving the eccentric wheel on its output shaft; as the motor rotates, the eccentric wheel is tangent to the folding edge of the locking slide plate, pushing it forward; the lock slide carries the lock slide forward, and the baffle on the lock handle is released (previously stuck in the groove of the lock slider); the handle is turned to drive the gear output shaft to make the heaven and earth poles expand and contract. In order to close the cabinet door, reset the lock handle and press it down. The front of the lock slide is equipped with a spring; thus, the lock slide will automatically rebound to bite the baffle, and the cabinet lock will be in a locked state.

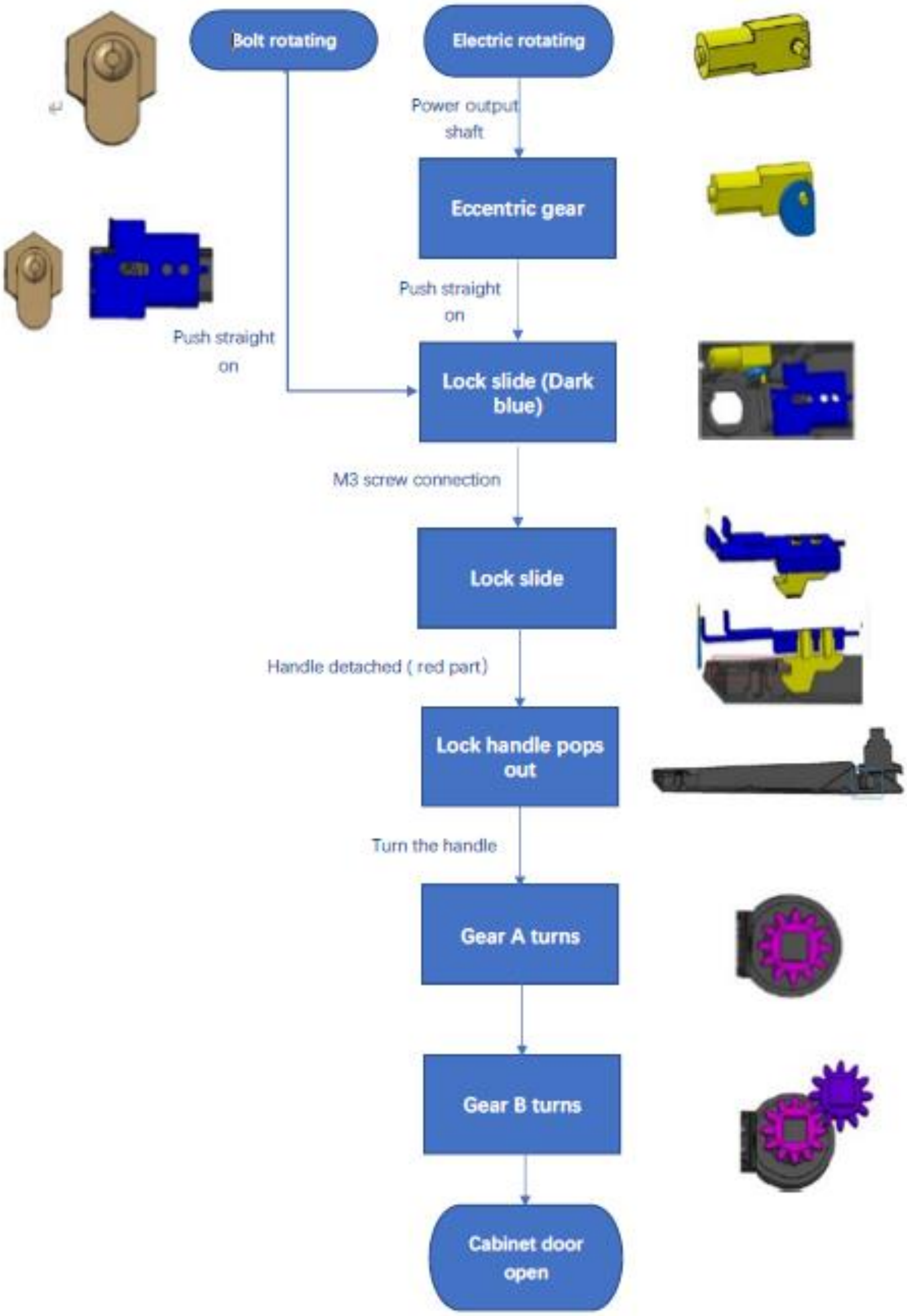
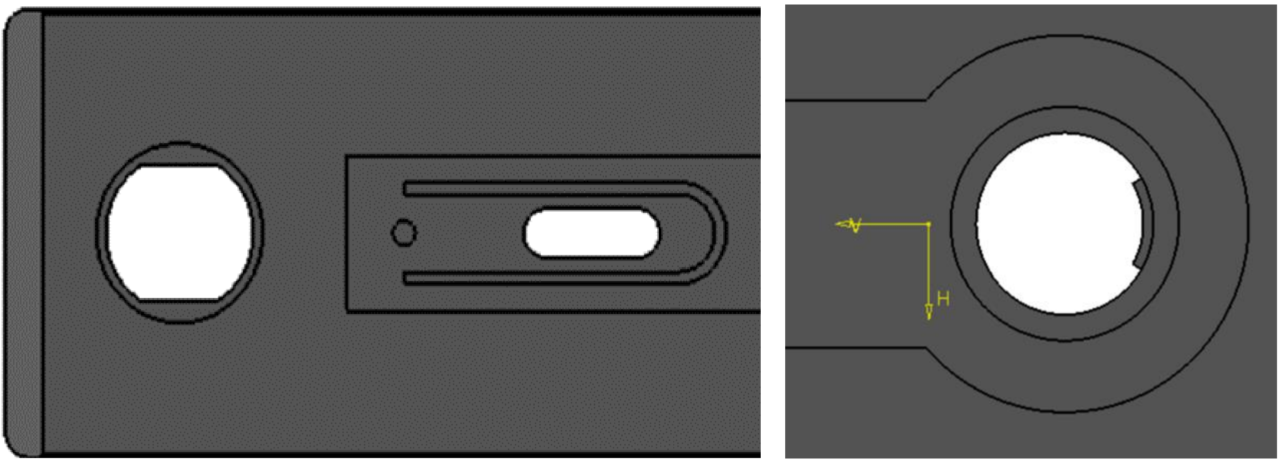


Figure 4. Mechanical transmission process

3.3.2. Transmission design details

For the integrated mechanical transmission device, the key structure details can be introduced, as shown in **Figure 5**, which is a three-dimensional diagram of two important lock bases. The function of the U-shaped column and small cylinder as shown in **(a)** is to prevent the iron wire from extending (the gap between the lock handle and the base), thus pushing the lock slider to release the handle. The arc with a 60-degree angle protruding from the circular hole as shown in **(b)** is used to buckle the lock handle to prevent the lock handle from popping out (under normal working conditions).



(a) **(b)**

Figure 5. Main lock bases

The gears of the mechanical transmission device are the main transmission parts. The main gear components are shown in **Figure 6**. The hole design of the double driven wheel conforms to the left and right opening of the cabinet door.

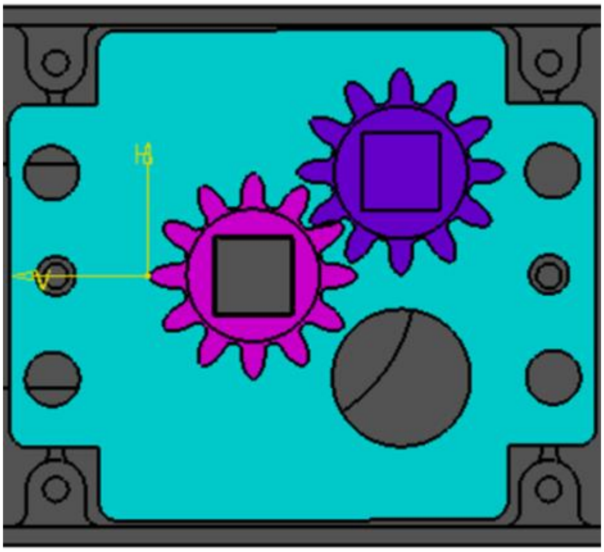


Figure 6. Structural diagram of main gear components

3.4. Finger vein module

The finger vein module recognition needs to acquire the characteristics of a person's finger veins. The existing finger vein acquisition methods include contact finger vein acquisition and non-contact finger vein acquisition. Among them, the contact finger vein acquisition method uses near-infrared laser, allowing the finger to be in direct contact with the LED light to acquire information about the vein, as shown in **Figure 7** [6]. The blood in the vein will absorb infrared rays of a specific wavelength; thus, it is possible to obtain the image of the vein. The whole process is a non-contact process. The principle is shown in **Figure 8** [3].

Figure 7. Contact finger vein acquisition method

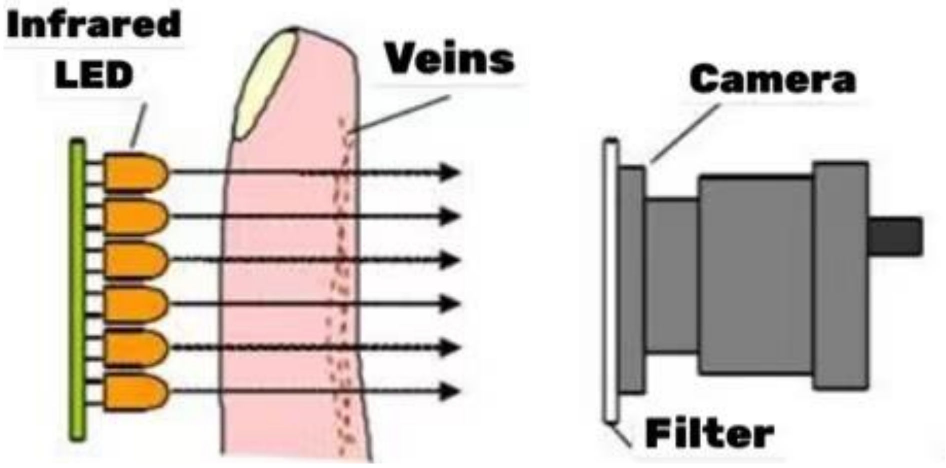
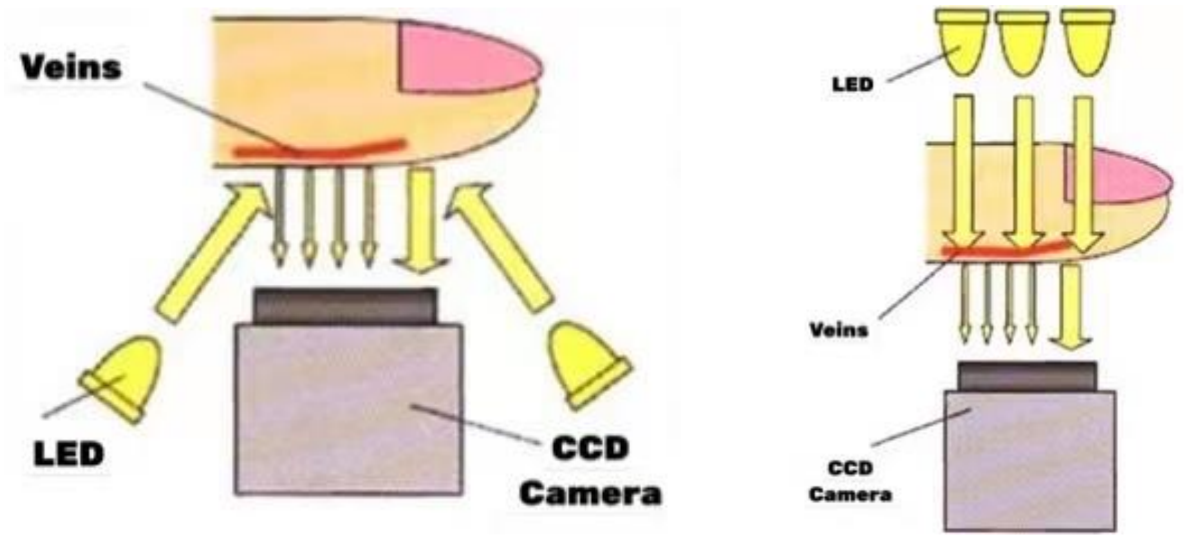


Figure 8. Principle of non-contact finger vein acquisition method

The finger vein acquisition method of the smart cabinet lock developed in this study is the contact finger vein acquisition. The finger vein recognition technology consists of four parts: image collection, image preprocessing, feature extraction, and matching [4]. With near-infrared light irradiation, the difference in the transmission of near-infrared light between hemoglobin in blood vessels and surrounding muscles as well as tissues is used to form finger vein images. Finger vein image acquisition methods include two methods: light reflection and light transmission (**Figure 9**). The difference between the two methods lies in the position where the near-infrared light module is placed. In the light reflection type, the camera and the near-infrared light module are positioned on the same side of the finger, while in the light transmission type, the camera and the near-infrared light module are positioned on the opposite side of the finger. Image acquisition is the basis of vein recognition. It is necessary to continuously explore new acquisition methods and optimize the equipment required for acquisition to improve the clarity of the image, thereby improving the accuracy of recognition. At the same time, the sensitivity of the sensor also has an impact on the acquired images. If the sensitivity is low, the image acquisition time is longer, resulting in distortion of the placed fingers. In addition, the equipment used for image acquisition requires a clever design that can fix the finger without affecting the acquisition of image. Therefore, this study adopts a unique reflection dispersion method, where the near-infrared light emitted by the LED is reflected inside the finger, and the vein pattern is captured by a CMOS (complementary metal-oxide-semiconductor) sensor.



(a) Light reflection (b) Light transmission

Figure 9. Digital vein image acquisition method

The original image of finger vein is acquired via image acquisition technology. The acquisition process is affected by factors such as complex environment, which may easily cause the acquired images to have low definition and large differences in brightness, thus affecting the recognition accuracy. In addition, the acquired image contains the finger vein area and the background area. Invalid information in the background area will interfere with the recognition of core information of the finger vein area. It will increase the storage length of the finger vein information, which will cause more difficulty in recognition each time the finger is placed there. The difference in the terminal position will also cause the image to be inclined or displaced, resulting in a large difference between the two images acquired before and after comparison and verification. This further hinders the identification of finger vein information. Therefore, it is necessary to filter the acquired original images.

Upon processing the image via the image positioning technology, feature extraction is performed on the finger vein image to obtain a feature map. Each finger vein has different lines, textures, and minutiae features. Finger vein lines refer to extracting the vein network from the gray image and using the vein network for recognition. This type of feature can better express the vein and the overall topological structure [7]. Finally, the feature image is compared and matched with the original template of the database, and the correlation can be calculated.

In this article, the aforementioned finger vein acquisition module, image processing module, feature extraction, and matching module are integrated into the finger vein recognition module. The finger vein recognition module is light and compact, but has fast response, high accuracy, comfortable use, with embedded functions of other machines, such as ATMs, safes, and cabinets. It supports USB and RS-232C interfaces, as well as its secondary development. The finger vein recognition module can be directly integrated into the smart lock, and the integrated finger vein recognition module can be directly considered when designing the shell of the smart lock.

3.5. 3D model

According to the above structural design, it can be confirmed that the overall structure of the smart lock includes an integrated unlocking method, namely a hybrid mechanical transmission device, a finger vein recognition module, and a housing device. The housing device is based on the internal mechanical transmission device, the finger vein recognition module, and the necessary hardware. According to the above structure, the internal layout plan of the smart lock based on finger vein technology can be determined as shown in **Figure 10**.

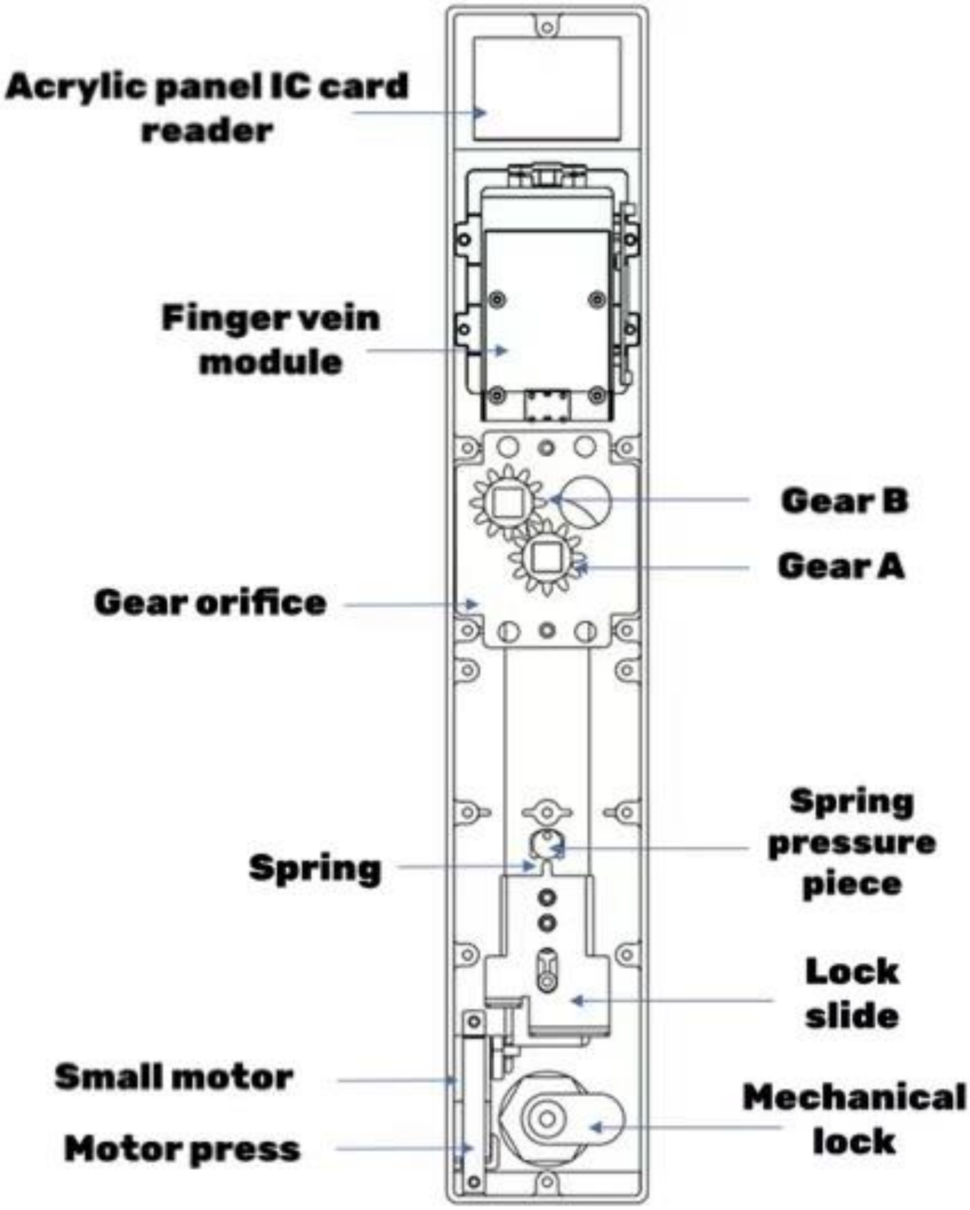


Figure 10. Internal layout

According to the layout plan of the smart lock shown in **Figure 10**, the internal components from top to bottom include an acrylic IC card read-write panel, finger vein module, a gear orifice plate with gear A and gear B, a spring with a spring pressure piece, lock slide plate, small motor, motor pressure piece, and a mechanical lock. The above-mentioned components are located inside the smart lock, and the overall structure of the smart lock can be confirmed based on these components. The housing device is then designed according to the internal parts. The final design of the three-dimensional model of the multifunctional smart lock shell is shown in **Figure 11**. The maximum length, width, and height of the design are as follows: 32 mm x 55 mm x 36 mm. On the other hand, the two-dimensional model of the layout of the parts on the shell is as shown in **Figure 12**.

Figure 11. 3D model of multifunctional cabinet lock

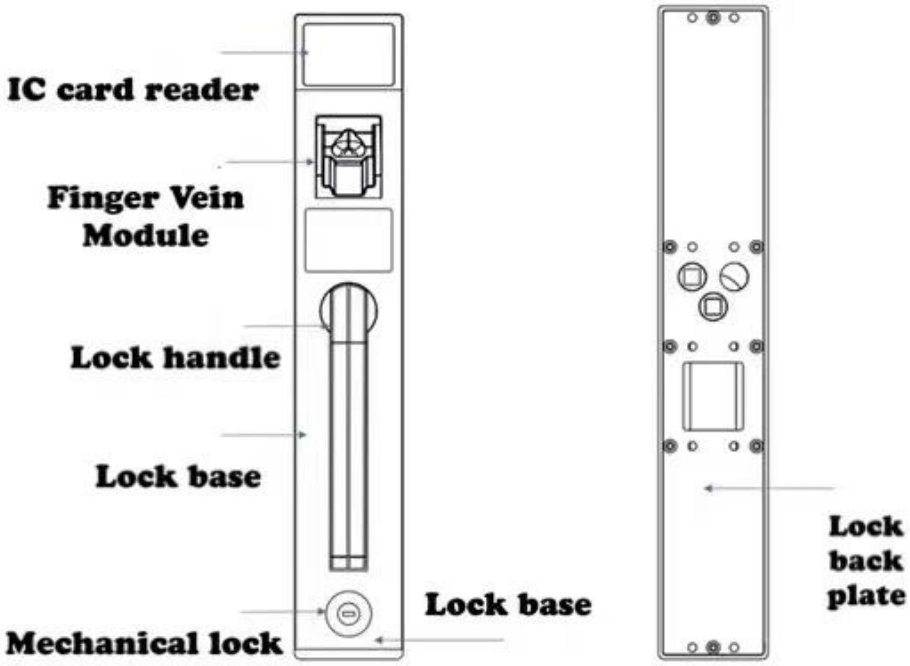


Figure 12. Layout plan of the parts on the shell

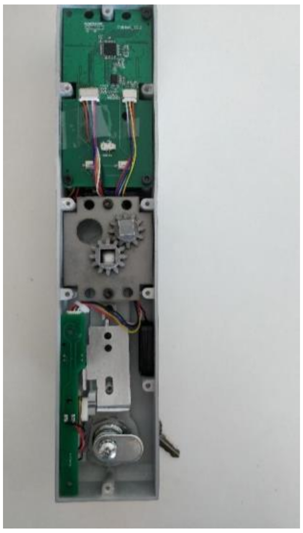
According to the two-dimensional layout of the parts in **Figure 12**, the front housing parts include an acrylic panel (swiping place), a finger vein module, a lock handle, a lock base, and a mechanical lock; at the back, it only has a lock back plate and some connections. However, there are registration and factory reset keys on the back of the lock body, and the cabinet lock is powered by a battery box installed inside the hole on the back.

4. Physical test

4.1. Physical display

According to the above design, the metal parts are machined, the resin material parts are 3D printed, and the necessary standard parts, hardware, and circuits are purchased. Finally, the parts can be assembled to produce a multifunctional smart lock based on finger vein technology. The actual product is shown in **Figure 13**.

(a) Front view



(b) Internal view

Figure 13. Smart lock based on finger vein technology

4.2. Unlocking process

According to **Figure 13**, the multifunctional cabinet lock controls the motor through the development board. The unlocking process of the control motor is shown in **Figure 14**. First of all, two types of acquisition methods (IC/ID card reading and finger vein acquisition) are used to acquire signals as signal input. Then, the same processor will determine whether the input signal is authorized; if authorized, it will be fed back to the motor control module through the information feedback module. The motor control module controls the unlocking, and finally realizes the unlocking function. However, if it is not authorized, an error signal will be returned through the information feedback module. In that case, the authorization signal needs to be re-input, and the signal is acquired again for verification.

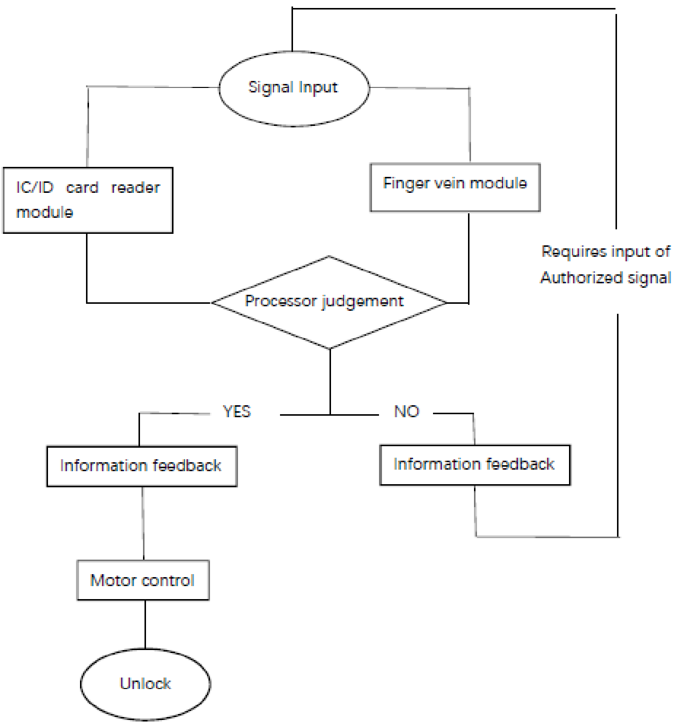


Figure 14. Unlocking process

4.3. Physical function test results

4.3.1. Structure size test

The overall design requirements of the multifunctional smart lock in this study are as follows: the length, width, and height are less than 340 mm x 60 mm x 40 mm. Measured with real objects, the overall size of the smart cabinet lock designed in this study is 328.4 mm x 55.12 mm x 35.89 mm, which meets the design requirements.

4.3.2. Unlocking method test

The most important aspect in terms of the functional requirements of the smart lock designed in this study is the integrated unlocking method, which requires multiple unlocking methods, including IC/ID card unlocking, finger vein unlocking, and mechanical key unlocking. In regard to the three unlocking methods, the product's unlocking function is tested.

First, the IC card unlocking method is tested. Since it is not the main method, only a few passes are required; it is not necessary to perform multiple tests for it. Following that, the finger vein unlocking method, which is the main unlocking method of the smart lock designed in this article, is tested. Multiple tests are required for comparison and verification. Therefore, 100 different human finger vein information were registered, and 100 tests were performed on the registered information, with a total of 99 times being successful, achieving a success rate of 99%. A total of 100 tests were carried out for unregistered finger veins. None of it was successful, with a failure rate of 100%. Therefore, the finger vein unlocking function passed. Finally, the mechanical key unlocking method is tested in emergency situations, and similarly, it passed.

4.3.3. Two-way unlocking test

This refers to the steering function requirements of the smart lock, in which it can be opened to the left and to the right according to different gear assembly positions. Therefore, it is necessary to test the door-opening function of the smart lock.

Physical tests were performed on the left and right doors of the smart lock. The tests found that the smart lock can turn left to drive the heaven and earth rod to expand and contract; the smart lock can also turn right to drive the heaven and earth rod to expand and contract. Therefore, the two-way steering function of the smart cabinet lock is required to pass.

5. Conclusion and prospects

5.1. Conclusion

A multifunctional smart cabinet lock based on finger vein technology has been developed in this study. Its overall structure includes a finger vein module, a lock control body, and an operating system. First, by confirming its unlocking method, improving the structural design and transmission method of unlocking, integrating the unlocking method, confirming the internal structure, transmission device, and component layout, followed by confirming the cabinet lock housing structure according to the internal parts and hardware, and finally obtaining a three-dimensional structure model, the smart cabinet lock is processed and assembled, and its function is tested. The test results indicate that the structure size of the smart lock designed in this study meets the design requirements; the unlocking method requires three unlocking methods: finger vein unlocking, IC/ID card unlocking, and mechanical key unlocking; the left and right door-opening function meets the left and right opening methods; the two-way unlocking meets the originally set R&D target and project requirements.

5.2. Prospects

The smart lock finger vein system designed in this paper is compact in structure and complete in terms of its functions. It reaches the initially set R&D goals and meets the initial project requirements. However, due to professional restrictions, there are still some deficiencies in its appearance factor, such as its aesthetics. Therefore, the second generation of smart locks will need to be improved in terms of aesthetics.

Disclosure statement

The author declares no conflict of interest.

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