



Embedded System

Design of Footwear Storage Control System with Fingerprint Based on Microcontroller

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A B S T R A C T

The issue of misplaced and stolen footwear in public spaces is a frequent problem that causes inconvenience to many people. This thesis aims to design and implement a smart locker system for footwear storage that uses biometric fingerprint security and is controlled by a microcontroller. The system integrates several key components: an AS608 fingerprint sensor for user authentication, an HC-SR04 ultrasonic sensor to detect if the locker is occupied, and an SW-420 vibration sensor to detect suspicious activity, such as forced entry. An ESP32 microcontroller serves as the central control unit, processing data from all sensors and managing the solenoid lock mechanisms via relays. Additionally, the system sends security alerts through a Telegram bot to the administrator. Based on the test results, the system successfully performs all its functions. The fingerprint sensor accurately handles both enrollment and matching processes. The ultrasonic sensor automatically and accurately detects the locker's status (empty/occupied). The vibration sensor effectively sends alert notifications when suspicious vibrations are detected. In conclusion, the implemented system is proven to be functional and an effective solution for improving the security and convenience of footwear storage in public areas.

INTRODUCTION

The problem of lost or swapped footwear in public places is a common phenomenon that affects many people [1][2][3]. According to a survey, 80.6% of respondents have directly experienced this problem, and 94% agree that this issue needs to be resolved. This problem has a significant impact on various aspects, including material loss (economic aspect), unethical theft (ethical aspect), and the risk of injury and infection (health and safety aspects).

Conventional solutions such as numbered racks and CCTV surveillance have proven to be less effective because they are reactive and depend on human supervision. To address this gap, a new, more automated and reliable approach is needed. Based on the needs analysis, the proposed solution must be able to accurately identify the footwear owner, detect indications of theft, and provide automatic security notifications. Related research on fingerprint recognition systems and the use of the ESP32 microcontroller for web-based monitoring serves as a theoretical basis for the development of this system, demonstrating the feasibility of using such technology.

METHOD

This research implements an engineering-based method to design a footwear storage locker control system with biometric fingerprint security based on microcontroller. The system is designed using several main components that work together to provide secure and efficient locker management. At the core of the system is the ESP32 microcontroller, which serves as the main processing unit and is selected for its dual-core processor, large memory capacity (520 KB SRAM and 4 MB Flash), and built-in Wi-Fi and Bluetooth modules that enable wireless connectivity. User authentication is carried out using the AS608 fingerprint sensor, an optical device that employs the Minutiae Template Matching method with an imaging time of less than one second and a storage capacity of up to 162 templates. For access control, a 12V DC solenoid lock is used as the door actuator, operated through a 4-channel relay that functions as an electronic switch. Security is further enhanced by the SW-420 vibration sensor, which detects abnormal shocks or vibrations that may indicate break-in attempts, and the HC-SR04 ultrasonic sensor, which measures distance to identify the presence of footwear inside the locker. For user interaction, a 4x4 keypad and a 20x4 LCD are integrated as input and output interfaces. The system is programmed and developed using the Arduino IDE, while a

Telegram Bot is implemented to provide real-time security notifications to users.

System Architecture Design

The hardware architecture of the footwear storage control system is designed to integrate security components, sensors, and user interfaces into a compact cabinet structure. The overall physical arrangement of the cabinet and control unit is shown in Figure 1.

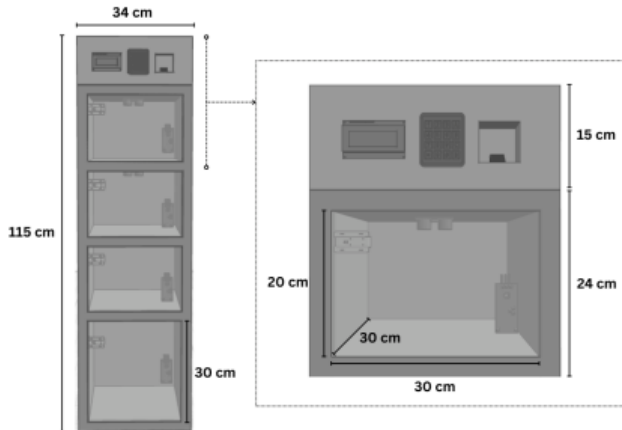


Figure 1 Hardware Design

Figure 1 illustrates the physical design of the footwear storage control system. The system is designed within a wooden cabinet with four storage. The cabinet consists of three compartments, each equipped with a solenoid lock, vibration sensor (SW-420), and ultrasonic sensor (HC-SR04) for security and occupancy detection. The main control box, placed on top of the cabinet, houses the ESP32 microcontroller and relay module as the core processing and actuation units. On the exterior of this control box, the fingerprint sensor, keypad, and LCD display are mounted to provide user interaction for locker registration and access. Dimensional details of both the cabinet and the compartment are provided to clarify the system's physical layout and spatial configuration.

This architecture is based on a block model, where input devices trigger data processing by the ESP32, which then controls the output devices. To illustrate the interaction between input devices, processing unit, and output devices, the system model is represented in a block diagram as shown in Figure 2.

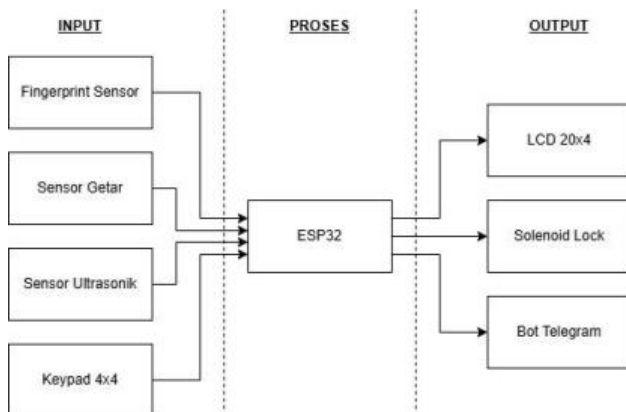


Figure 2 Block Diagram

Figure 2 presents the overall system architecture, where multiple input devices including the fingerprint sensor, vibration sensor,

ultrasonic sensor, and 4x4 keypad provide data to the ESP32 microcontroller as the central processing unit. The ESP32 then controls the output components, namely the LCD 20x4 for user interface, the solenoid lock for access control, and the Telegram bot for remote monitoring and notifications.

To implement the footwear storage control system, the hardware components are interconnected based on the wiring configuration illustrated in Figure 3.

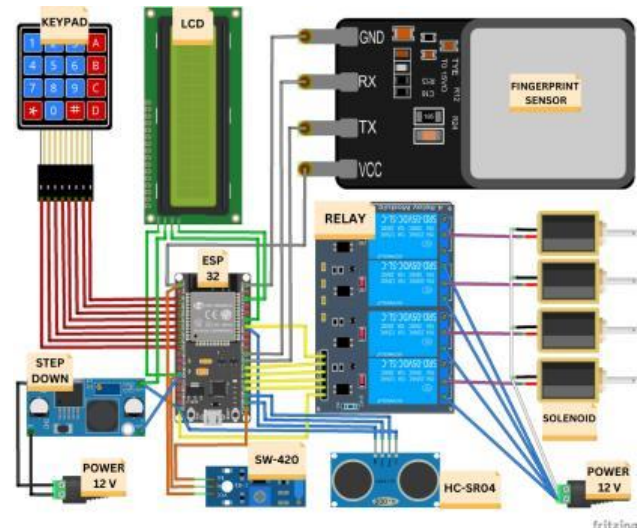


Figure 3 Schematic Circuit

Figure 3 shows the detailed schematic diagram of the system, where the ESP32 microcontroller serves as the central controller connected to the fingerprint sensor, 4x4 keypad, ultrasonic sensor (HC-SR04), and vibration sensor (SW-420) as inputs. The outputs are managed through a relay module that controls the solenoid locks, while the LCD provides real-time display for users. A step-down power module is used to regulate voltage, and the entire system is powered by a 12V supply to ensure stable operation of all components.

To describe the workflow of the footwear storage control system, a general system flowchart is presented in Figure 4.



Figure 4 General System Flowchart

Figure 4 illustrates the overall process of the system, starting with the initialization of components and Wi-Fi connection, followed by status detection of each locker. The system then calculates the number of available and occupied lockers, displays the locker status, and executes locker functions as well as intrusion detection processes. The flow concludes with the system providing feedback and ensuring secure operation.

To explain the operational logic of the locker system, a detailed flowchart of the locker function process is presented in Figure 5.

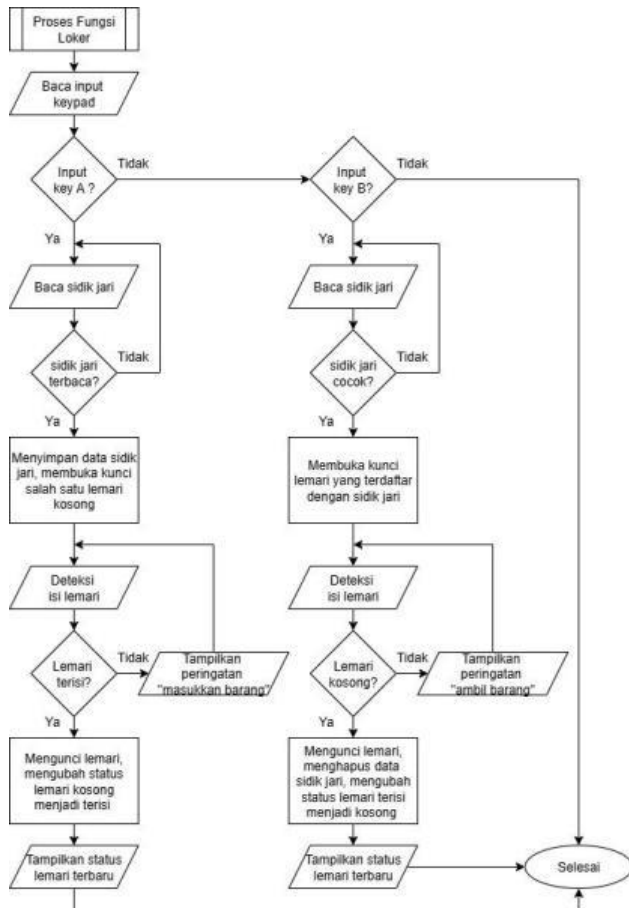


Figure 5 Sub-process of Locker Functionality

Figure 5 illustrates the sub-process of locker functionality, which describes the interaction mechanism between users and the system based on keypad input and fingerprint authentication. The process begins with keypad input, where two options are available: key A for new user registration and key B for returning users to access their assigned locker.

When key A is pressed, the system reads a new fingerprint. If the fingerprint is successfully captured, the data is stored in the sensor memory and one of the empty lockers is opened. The system then performs occupancy detection to verify whether the locker has been filled. If the locker is occupied, it is automatically locked, the status is updated to “occupied,” and the fingerprint data is saved. If the locker remains empty, the system displays a “place item” warning until the user deposits their belongings. The updated locker status is then shown on the LCD.

On the other hand, if key B is pressed, the system reads and matches the fingerprint against the stored data. If the fingerprint

matches, the locker associated with that fingerprint is unlocked. Afterward, occupancy detection is performed. If the locker is empty, the system deletes the user’s fingerprint data, changes the locker status to “empty,” and locks it again. If the locker is still occupied, the system displays a “take item” warning until the belongings are retrieved. The latest locker status is then updated and displayed on the LCD.

This sub-process demonstrates how the system manages two main usage scenarios: fingerprint enrolment for new users during footwear storage, and fingerprint matching for registered users during item retrieval. The integration of occupancy detection ensures that locker status is consistently updated and accurate.

To enhance security, the system includes a sub-process for detecting potential break-in attempts, which is illustrated in Figure 6.



Figure 6 Sub-process of break-in attempts Detection

Figure 6 shows the sub-process for intrusion detection based on vibration analysis at the locker door. The process begins with vibration detection using a vibration sensor on each locker door. The detected vibrations are then compared with a predefined threshold of two occurrences. If the number of vibrations is less than or equal to the threshold, the system continues monitoring. However, if the number of vibrations exceeds the threshold, the system interprets it as a potential break-in attempt and processes the data to be sent to the Telegram application via a programmed bot. This enables real-time communication between the locker system and the user or administrator, where the Telegram bot displays a warning notification indicating suspicious activity. Thus, this sub-process acts as an additional security mechanism that provides early alerts against potential tampering with the locker.

Testing Methodology

Testing was conducted in two stages: unit testing for each component (fingerprint sensor, ultrasonic, vibration, and *solenoid lock*) and overall functionality testing. Unit testing verified whether each component worked according to specifications. Overall functionality testing, such as scenarios for depositing, retrieving, and security detection, verified the integration between components and ensured the system operated as intended.

RESULTS AND DISCUSSION

In the implementation of this system, the installation of components is carried out in two parts, namely in the storage cabinet and in the control box located on top of the cabinet, as shown in Figure 7.

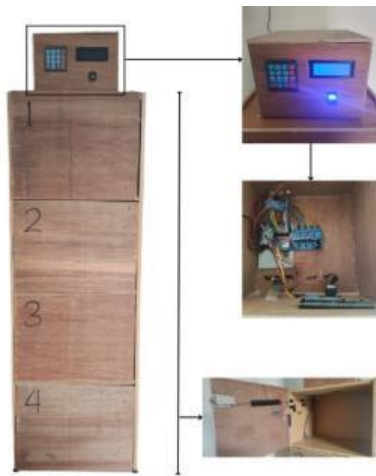


Figure 7 Hardware Implementation

The implementation of the Telegram bot was carried out using the official service provided by Telegram, namely BotFather. Once the bot is created, it can be utilized according to its intended function. The security notification message of this system can be observed through the Telegram interface, as shown in Figure 8.



By sending the /start command, the bot begins its operation. The bot receives signals from the microcontroller so that when the vibration sensor detects unusual vibrations, a notification message is delivered to the Telegram bot.

Testing and Analysis

The testing of the storage locker control system was conducted to ensure that each component functions according to the specified requirements and achieves the intended objectives. Each component was tested under predetermined environmental conditions. In this way, it is expected that all components within the system can operate optimally in accordance with their specifications, thereby fulfilling the design objectives of the system.

Fingerprint Sensor Testing

The testing method was carried out to evaluate the fingerprint enrollment and matching functions of the locker system. The procedure began with the initialization of the ESP32 and AS608 fingerprint sensor, followed by enrollment trials using five different fingerprints. Each fingerprint was enrolled by capturing two images in sequence, and the results were recorded as either successful or failed enrollment. Subsequently, matching trials were performed by verifying the fingerprints that had been successfully stored in the sensor's memory. The outcomes of each trial, including enrollment and matching attempts, were documented in a structured table for analysis.

Table 1 Fingerprint Sensor Testing

Trial No.	Fingerprint No.	Detection Result	Remarks
1	#1	Fingerprint successfully enrolled	Successful Enrollment
2	#2	Fingerprint successfully enrolled	Successful Enrollment
3	#3	Fingerprint successfully enrolled	Successful Enrollment
4	#4	Fingerprint successfully enrolled	Successful Enrollment
5	#5	Fingerprint enrollment failed	Failed
6	#1	Fingerprint already registered	Successful Matching
7	#2	Fingerprint already registered	Successful Matching
8	#3	Fingerprint already registered	Successful Matching
9	#4	Fingerprint already registered	Successful Matching
10	#5	Fingerprint enrollment failed	Failed

Based on the test results from Table 1, a total of six enrollment attempts were conducted, of which four were successful and two failed, yielding an enrollment success rate of 66.7%. In contrast, all four matching attempts were successful, resulting in a 100% success rate for fingerprint recognition of previously enrolled templates. The two failures in enrollment occurred with Fingerprint #5, which indicates sensitivity to image quality, finger placement, or electrical stability during the enrollment

process. Overall, the system achieved an 80% success rate across all ten trials. These findings demonstrate that the fingerprint matching function works reliably, while improvements are needed in the enrollment process, such as guiding users for proper finger placement, ensuring sensor cleanliness, and providing stable power supply. Thus, the test confirms that the system can perform fingerprint-based authentication effectively, with enrollment being the main aspect requiring optimization.

Ultrasonic Sensor Testing

The testing was conducted to evaluate the performance of the HC-SR04 ultrasonic sensors in detecting the occupancy status of each locker compartment. Four ultrasonic sensors were installed inside the lockers, each positioned to measure the distance between the sensor and the stored footwear. The test procedure involved two scenarios for each sensor: the locker being empty and the locker being occupied with footwear. In the empty condition, the expected distance reading should be greater than 30 cm, which corresponds to the unobstructed space of the locker. In the occupied condition, the expected distance should be significantly shorter, depending on the placement of the footwear, typically less than 15 cm. Each measurement was recorded in terms of the detected distance (in centimeters) and compared with the actual condition of the locker. The detection result was then classified as either “Empty” or “Occupied” and validated against the actual state to determine the accuracy of the system.

Table 2 Ultrasonic Sensor Testing

Trial No.	Sensor No.	Actual Condition	Detected Distance	Detection Result	Remarks
1	#1	Empty	34 cm	Empty	Correct
2		Occupied	11 cm	Occupied	Correct
3	#2	Empty	34 cm	Empty	Correct
4		Occupied	11 cm	Occupied	Correct
5	#3	Empty	35 cm	Empty	Correct
6		Occupied	28 cm	Occupied	Correct
7	#4	Empty	34 cm	Empty	Correct
8		Occupied	8 cm	Occupied	Correct

The results from Table 2 showed that all eight trials produced outcomes consistent with the actual locker conditions. When the lockers were empty, the sensors detected distances in the range of 34–35 cm, which correctly corresponded to the “Empty” status. Conversely, when the lockers were occupied, the detected distances ranged between 8 cm and 28 cm, and all were correctly classified as “Occupied.” This indicates that the system successfully distinguished between empty and occupied states for each locker, with an overall accuracy of 100% across the trials. These findings confirm that the ultrasonic sensors function reliably in this application, with the threshold distance of approximately 30 cm serving as an effective boundary for classification. The consistent performance across multiple sensors also demonstrates robustness, suggesting that the detection method is suitable for real-time locker monitoring.

Vibration Sensor Testing

The testing was conducted to evaluate the performance of the SW-420 vibration sensor in detecting abnormal vibrations on locker doors as an indication of potential break-in attempts. Each locker door was equipped with one vibration sensor, and the experiment was performed on four sensors (Sensor #1–#4). For

each trial, the vibration sensor output was read three times in sequence to capture possible fluctuations. The output of the sensor was recorded in binary form: HIGH (1) indicating vibration detected and LOW (0) indicating no vibration. The total number of HIGH signals in each trial was then calculated and compared with a predefined threshold. The threshold was set to three vibrations; thus, if the total vibration count reached three within 10 seconds, the system classified the event as a “Break-in Indication.” If the vibration count was fewer than three, the system classified the event as a “Safe Condition.” A total of sixteen trials were conducted, consisting of four sets of measurements for each sensor.

Table 3 Vibration Sensor Testing

Trial No.	Vibration Value 1	Vibration Value 2	Vibration Value 3	Total Vibrations	Remarks
1	LOW (0)	LOW (0)	LOW (0)	0	Safe Condition
2	HIGH (1)	LOW (0)	LOW (0)	1	Safe Condition
3	HIGH (1)	HIGH (1)	LOW (0)	2	Safe Condition
4	HIGH (1)	HIGH (1)	HIGH (1)	3	Break-in Indication
5	LOW (0)	LOW (0)	LOW (0)	0	Safe Condition
6	HIGH (1)	LOW (0)	LOW (0)	1	Safe Condition
7	HIGH (1)	HIGH (1)	LOW (0)	2	Safe Condition
8	HIGH (1)	HIGH (1)	HIGH (1)	3	Break-in Indication
9	LOW (0)	LOW (0)	LOW (0)	0	Safe Condition
10	HIGH (1)	LOW (0)	LOW (0)	1	Safe Condition
11	HIGH (1)	HIGH (1)	LOW (0)	2	Safe Condition
12	HIGH (1)	HIGH (1)	HIGH (1)	3	Break-in Indication
13	LOW (0)	LOW (0)	LOW (0)	0	Safe Condition
14	HIGH (1)	LOW (0)	LOW (0)	1	Safe Condition
15	HIGH (1)	HIGH (1)	LOW (0)	2	Safe Condition
16	HIGH (1)	HIGH (1)	HIGH (1)	3	Break-in Indication

The test results from Table 3 demonstrated consistent performance across all four sensors. In trials where no or only one to two vibrations were detected, the system classified the condition as safe, which aligns with the actual state of the locker. In contrast, when all three readings indicated vibration (total count = 3), the system correctly identified the condition as a potential break-in attempt. This behavior was observed consistently in trials 4, 8, 12, and 16 across different sensors, showing that the threshold-based method effectively distinguishes between normal and abnormal vibrations. Overall, the system achieved 100% accuracy in classifying safe and break-

in conditions within the scope of the experiment. These findings confirm that the SW-420 sensor, when integrated with the threshold-based detection logic, is reliable for use as a complementary security mechanism in the locker system. Furthermore, the results highlight the potential of the system to provide early warnings of tampering or forced entry, particularly when coupled with real-time notifications via the Telegram bot.

Actuator Testing

The testing was carried out to verify the functionality of the solenoid lock system controlled by a 4-channel relay module. Each solenoid lock was connected to an individual relay channel (IN1–IN4) and tested sequentially. The procedure for each solenoid lock involved two conditions: activating the relay by setting its input to LOW (Active), which should result in the solenoid unlocking, and deactivating the relay by setting its input to HIGH (Inactive), which should return the solenoid to the locked state. During each trial, the relay status, the corresponding solenoid response, and the overall functionality were recorded. A total of eight trials were conducted, consisting of two tests for each of the four solenoid locks.

Table 4 Actuator Testing

Trial No.	Solenoid Lock No.	Relay Channel	Relay Status	Solenoid Response	Remarks
1	#1	IN1	LOW (Active)	Unlocked	Success
2		IN1	HIGH (Inactive)	Locked	Success
3	#2	IN2	LOW (Active)	Unlocked	Success
4		IN2	HIGH (Inactive)	Locked	Success
5	#3	IN3	LOW (Active)	Unlocked	Success
6		IN3	HIGH (Inactive)	Locked	Success
7	#4	IN4	LOW (Active)	Unlocked	Success
8		IN4	HIGH (Inactive)	Locked	Success

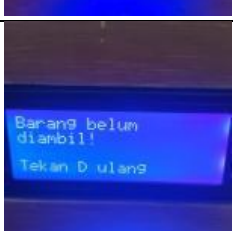
The results from Table 4 showed that all four solenoid locks functioned properly in response to relay control. When the relay input was set to LOW, the solenoid lock successfully transitioned to the unlocked state, and when the relay input was set to HIGH, the solenoid lock reliably returned to the locked state. This consistent performance was observed across all channels (IN1–IN4), indicating that both the relay module and solenoid locks operated in accordance with the system design. No failures were observed throughout the eight trials, confirming a 100% success rate for relay-to-solenoid actuation. These findings demonstrate that the relay module is effective in switching the solenoid locks, ensuring reliable operation for locker access control. Furthermore, the results validate the suitability of the relay–solenoid configuration for real-time implementation in the footwear locker system, where precise and dependable locking mechanisms are essential for security.

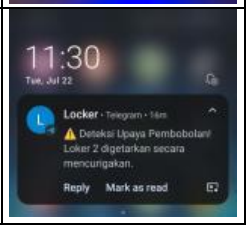
System Integration Testing

In conducting the overall system testing, three testing activities were carried out, namely the footwear deposit process, the footwear retrieval process, and the Telegram notification. Each testing activity involved several related components. The steps of each testing activity consisted of multiple scenarios, and for each scenario the expected results were defined. Subsequently, the outcomes obtained were analyzed to determine whether they matched the expected results for each scenario.

Table 5 System Integration Testing

Testing Scenario	Expected Result	Actual Result
Initial condition when user arrives	Ultrasonic sensor detects the status of each locker and the system calculates the number of available and occupied lockers. LCD displays locker status and further usage instructions.	
User presses button A on the keypad to deposit footwear	LCD displays instruction for the user to place a fingerprint on the sensor for registration.	
User places fingerprint twice on the fingerprint sensor	System maps the fingerprint to an available locker and unlocks its solenoid. LCD displays a successful registration message and further usage instructions.	 
User puts footwear inside the locker and presses button D	Solenoid lock re-locks the locker. LCD displays the updated locker status.	

User does not put footwear but still presses button D	LCD displays a warning that the user must insert footwear before the locker can be locked.	
User presses button A when all lockers are full	LCD displays a message that all lockers are occupied or registered.	
Initial condition, user presses button B	LCD displays instruction to place a fingerprint on the sensor.	
User places fingerprint on the sensor	System detects registered fingerprint, opens the corresponding locker, and LCD shows further instructions.	
User retrieves footwear and presses button D	Solenoid lock re-locks the locker, system deletes the fingerprint, and LCD shows updated status.	
User does not remove footwear but presses button D	LCD displays a warning that the user must remove footwear before the locker can be locked again.	
User presses button B when all lockers are empty	LCD displays a message instructing the user to register first by pressing button A.	

User places an unregistered fingerprint	LCD displays a message that the fingerprint is not recognized.	
Locker is shaken	Vibration sensor detects suspicious vibration and the system sends a warning notification to Telegram.	

Overall, the test results show that all main system functions operate properly and in accordance with the design, ranging from user interaction with the device, automatic locking, user fingerprint data management, to the security alert system. The system not only provides convenience in the deposit and retrieval of footwear but also ensures its security. The success of all testing scenarios indicates that the system is well-integrated and that the functionality of all involved components—namely the fingerprint sensor, ultrasonic sensor, vibration sensor, keypad, LCD, microcontroller, solenoid lock, and Telegram bot connection—works effectively.

CONCLUSIONS

1. The footwear storage locker control system with biometric fingerprint security has been successfully implemented according to the initial design, both technically and functionally.
2. The fingerprint sensor has fulfilled the system's primary security requirement by serving as the fingerprint authenticator in the processes of depositing and retrieving footwear in the storage locker.
3. The HC-SR04 ultrasonic sensor is capable of automatically and accurately detecting locker status, enabling the system to guide users to the available locker number.
4. The SW-420 vibration sensor can detect break-in attempts or suspicious vibrations, and the system automatically sends a notification to Telegram as a warning.
5. The system provides dual security through biometric fingerprint authentication and solenoid lock mechanisms, which can only be accessed by registered users according to the stored fingerprint data.

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