ESP32-Based Smart Storage System with Fingerprint and HMI Integration for Workspaces

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***Abstract*—Management of laboratory equipment in higher education institutions often faces challenges such as lack of supervision, difficulties in inventory tracking, and an unstructured system. To address these issues, this research designs a Laboratory Component Storage Management System that integrates fingerprint technology, proximity sensors, HMI, and a database. The proximity sensor shows a success rate of 75% in detecting objects up to a distance of 10 cm. The stepper motor system on the X, Y, and Z axes has an average error of less than 1%, supporting movement precision. The VB.NET-based interface has proven successful through black box testing, with an Admin borrowing time of 47–50 seconds and a User borrowing time of 55–70 seconds, as well as a return time of 42–45 seconds and 52–62 seconds, respectively. This system enhances security, efficiency, and user experience in the practical process and can be an alternative solution to the weakness of the manual inventory system in the laboratory.**

Keywords: Database integration introduction, Esp32, Fingerprint recognition, Practicum, Tool Management.

I. INTRODUCTION

HIGH education especially in engineering, places practicum as an integral part of the curriculum to provide practical experience to students. Practical activities are one of the academic activities that aim to observe, experiment, understand, and apply the theories obtained during lectures by practicing them inside and outside the laboratory [1]. However, the implementation of practicum is often hampered by the challenges of storing and borrowing practicum component tools, which can affect the student learning process.

Some of the obstacles that arise in the implementation of practicum include the absence of a system that supports borrowing and returning components, lack of student awareness in returning practicum component tools, limited storage space, and difficulty in knowing the availability of practicum tools and materials, lack of methods in collecting data that still use manual inputting and recording methods in managing inventory data storage [2]. Checking loan data is done every week through weekly reports, so if there is a loss of equipment on that day, before the weekly report is done it will be difficult to detect.

To overcome these problems, an innovative solution was formulated in the form of “Designing an Automatic Lending Smart System in the Workspace Using ESP32-Based Fingerprint and Human Machine Interface Integrated with Database”. This system carries a smart concept by utilizing Fingerprint Recognition to monitor the availability of practicum components in real time. An automated system can be applied to the process of storing and retrieving laboratory instruments so that the process is faster, easier, and has higher accuracy[3].

Robotic Process Automation (RPA) is also becoming an important element in the banking and finance sector, especially for loan processing and fraud detection. RPA can reduce operational costs by 30%-70% by replacing repetitive tasks, while improving efficiency and accuracy [4]. Through automated bots, financial institutions can simplify customer information collection, loan approval, credit monitoring, and pricing more efficiently.

Furthermore, machine learning technology has optimized the mortgage loan application process through the automation of document verification, predictive analytics for risk assessment, and high-accuracy fraud detection [5]. By leveraging large amounts of data, machine learning algorithms can predict borrower behavior more precisely than traditional methods, allowing lenders to make more informed decisions. With the solution we offer, it is hoped that students will no longer experience difficulties in borrowing and returning practicum component tools. In addition, this system will also make it easier for students to find out the availability of practicum tools and materials before carrying out practicum, so that practicum time can be utilized more efficiently. Through the application of technology in practicum management, it is expected to make a positive contribution to the quality of learning in higher education, especially in the context of practicum in engineering.

II. METHOD

A. Automated Storage

Research by Mustaqim Alhilal, M. Sohibul Hajah, and Akhmad Arif Kurdianto (2022) developed an online-based 3-axis ASR (Automated Storage and Retrieval) robot for instrument lending, controlled by a PLC and using proximity sensors for position detection. DC motors drive the robot on three axes, but multi-axis control requires a more complex system and additional sensors like encoders [3]. Research by Manisha Suresh Pingale and Dr. Haripriya H. Kulkarni (2019) designed an ASRS prototype for warehouses using IoT and Bluetooth communication [6]. However, Bluetooth's limitations in large warehouses can disrupt communication. Research by Hadisantoso, Feri Siswoyo, and Tamsir (2018) developed an Arduino-based storage and retrieval system using a web database, but lacked details on user access and data storage, which are important for security [7].

B. Use Case Diagram

A use case is a simple representation of the system that will be created. A use case diagram has three main parts, namely:

a) Actor: The parties involved in the system.

b) Use Case: Activities or features provided by the system or business.

c) Relationship/Link: The connection between the actor and the existing use case.

In addition, Use Case describes the external view of the system that will be modeled [8] .Modeling use cases helps understand user needs and how the system interacts with them, thereby forming the foundation for software development.

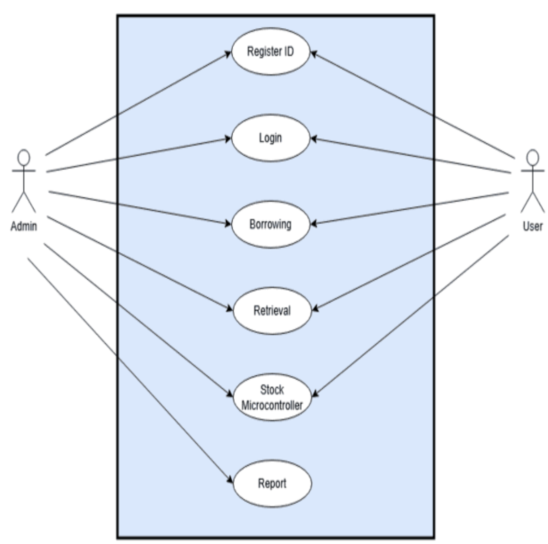

Figure 1. Use Case *Diagram.*

C. Flowchart

A flowchart is a diagram that shows the steps in completing a process or problem. With simple symbols, flowcharts help understand the sequence of tasks clearly and structurally. Flowcharts usually make it easier to solve a problem, especially problems that need to be studied and evaluated further [9]. Figure 2 shows a flowchart illustrating the system's workflow, starting with port configuration. After that, users are directed to the main menu, which provides three options: new ID registration, login for registered users, or checking the stock of microcontrollers. Each option will perform its respective function before the process ends.

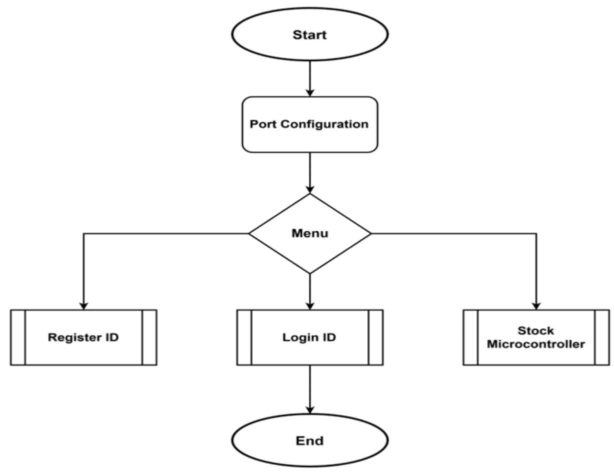

Figure 2. Flowchart Overall System.

Figure 3 shows the flowchart of the ID registration process, which includes two types of users, namely Admin, and User.

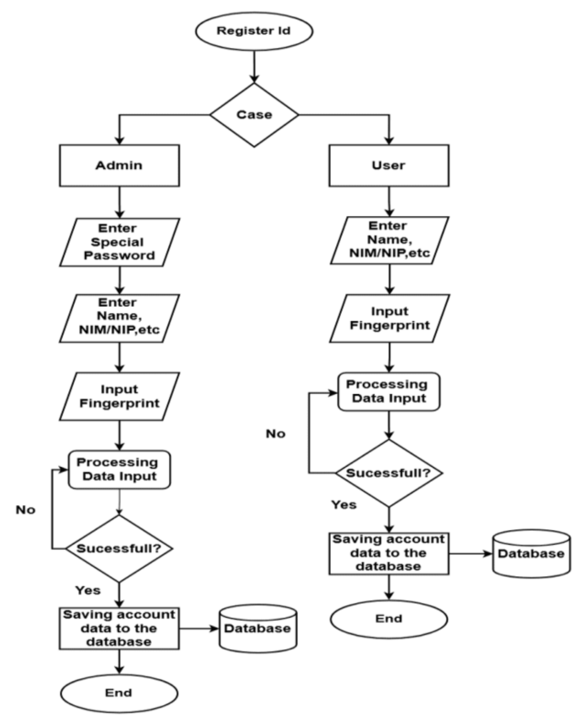

Figure 3. Register ID.

This process begins with the selection of user type, where the admin must enter a special password before inputting personal data and fingerprints, while the User directly inputs personal data and fingerprints. After the data is processed, the system will check its validity. If valid, the account information will be stored in the database, and the registration process will be complete. If invalid, the user must repeat the input process.

Figure 4 shows the flowchart Login ID process using fingerprints. The process begins with the user entering their fingerprint for verification. If the entered data is invalid, the system prompts the user to repeat the process. If the verification is successful, the system displays the user's fingerprint ID, saves the login activity into the database, and then displays the main menu before the process ends.

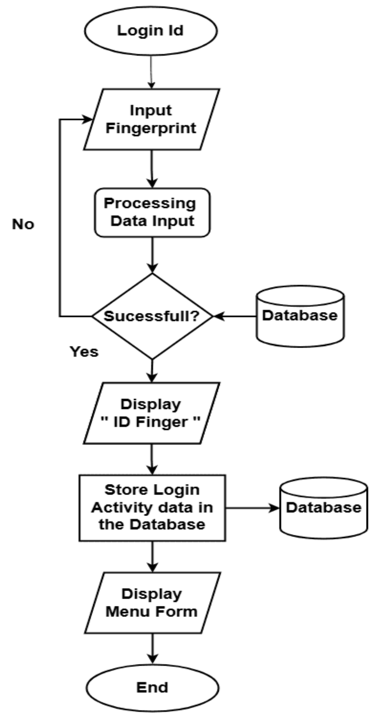

Figure 4. Login ID.

D. System Design

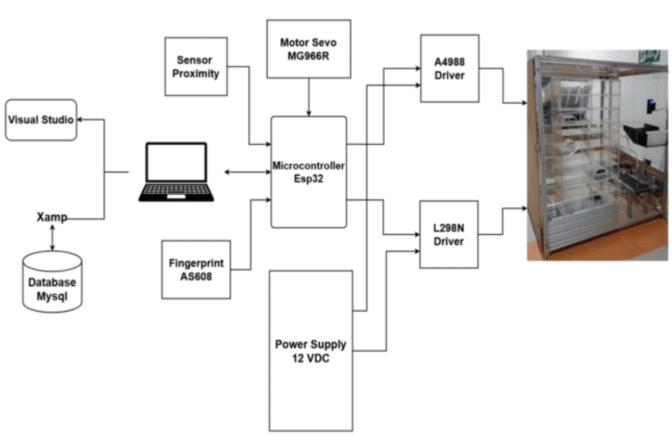

Figure 5. System Design.

Figure 5 shows an overview of the system designed to manage all system functions in an integrated manner.

The system uses a user interface that is created to access the functionality of this system and view the data of available items. The PC is connected to the Arduino via a USB serial connection, and the available COM ports are automatically detected.

The user interface is built with visual basic programming with a local server (localhost) as the operational base. Commands to the microcontroller that controls the motor driver, conveyor, clamp, and other menus are executed with a simple click on the interface. To take inventory of the data stored in the MySQL database, the user simply fills in the special data storage or retrieval menu.

E. Mechanical Design

The mechanical design of this workspace automated lending system is designed using a three-dimensional approach to accommodate efficient storage and retrieval of items. The main structure of the device has dimensions of 80 cm x 70 cm x 75 cm, with storage compartments organized in two columns and eight rows, providing sufficient capacity for various components such as Arduino or other devices.

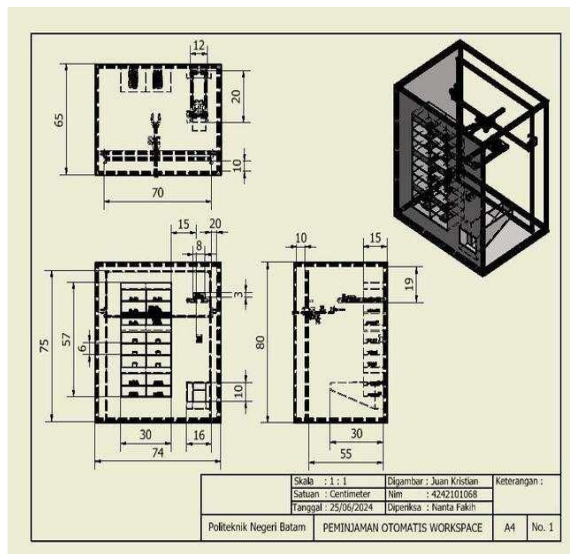

Figure 6. Mechanical Design.

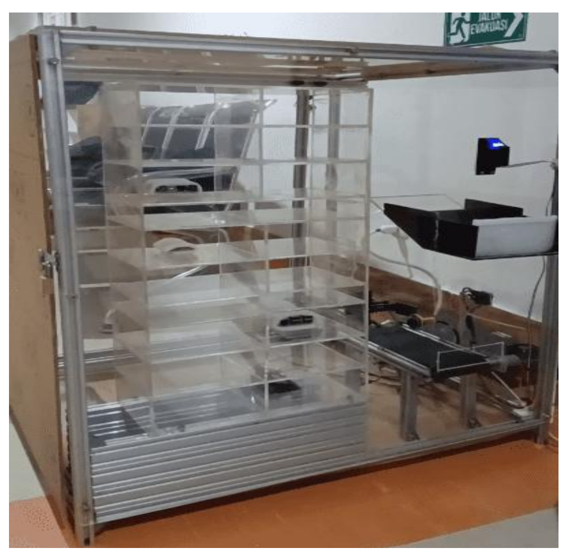

Figure 7. Actual Design.

The main component of the mechanism is a 3-axis motion system driven by a stepper motor. The system is equipped with clamps that can pinch items with precision, enabling high accuracy picking and placing of items on the shelves. This design ensures all components are reached automatically without the need for manual intervention.

In its implementation, the design is designed to be integrated with an ESP32-based fingerprint sensor that serves for user authentication, as well as a human-machine interface that makes it easier for users to operate the system.

The compact dimensions of the device ensure that the system can be placed in various types of workspaces without taking up much space. The rack scheme and motion mechanism are also designed to minimize the risk of damage to goods during the moving process. With a sturdy frame and standardized mechanisms, the design is expected to improve operational efficiency and provide an optimal user experience.

F. Electrical Design

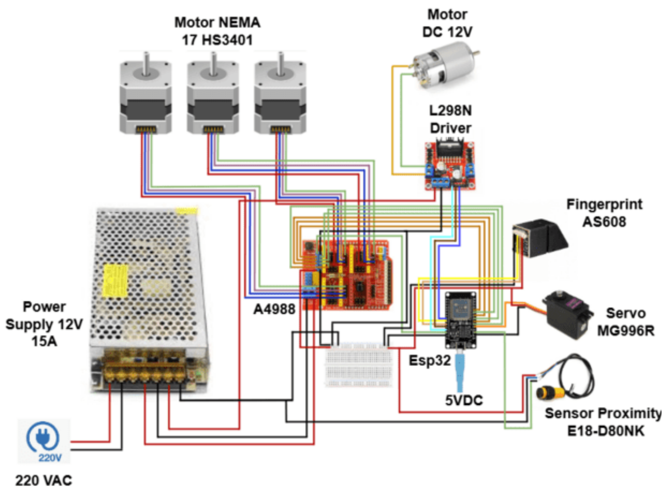

Figure 8. Electrical Design.

Figure 8 shows the ESP32-based motor control system circuit integrated with various components, including three stepper motors, a DC motor, a servo, and a fingerprint sensor. The system is designed to implement the function of borrowing and returning items using stepper motor coordination in the X, Y, and Z axes. Each stepper motor is controlled by an A4988 driver, which gets power from a 12V external voltage source. The connection line between the driver and ESP32 includes step and direction pins, which regulate the movement of the stepper motor according to the programmer command. In addition, the DC motor is controlled using an L298N motor driver, which also supports a servo for additional motion in this application.

On the user identification side, the system uses a fingerprint sensor module connected via serial communication (TX and RX) to the ESP32. This communication allows the sensor to read the user's fingerprint data and validate it with the database that has been integrated in the system. An additional 5V power supply is used to support the ESP32 and the fingerprint sensor for stable operation. This wiring design is designed with efficiency to maximize the control of multi-axis motors as well as the integration of sensor modules, to be able to carry out logical functions such as register, login, borrowing, and returning items based on user input through a pre-made programming interface.

G. User Interface Design

The user interface is the main point of interaction for accessing system functions**.** It serves as a representation of the interface in terms of both visual appearance and navigation within the system. One type of interface commonly used is the Human-Machine Interface (HMI), which is a tool that enables communication between humans and machines. HMI functions as a link between the operator and the system, which can be in the form of an LCD, PC monitor, Android device, or other screens[10].In this system, the HMI used is based on Visual Basic .NET software, designed to provide more intuitive control and interaction.

Designed for ease of use, it enables data input, monitoring, and control. Built with Visual Basic, the GUI sends commands to the microcontroller, managing motors, sensors, and storage. Secure access is ensured through fingerprint authentication, while real-time MySQL data retrieval monitors inventory and system performance.

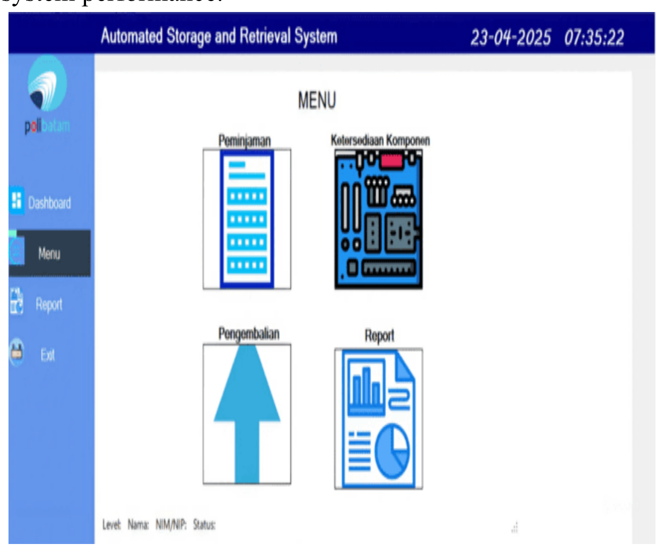

Figure 9. Main Menu Interface Design.

Figure 9 shows dashboard form serves as the main interface where users can view system status, access key functions, and monitor real-time data. It provides a clear layout for easy navigation and efficient operation.

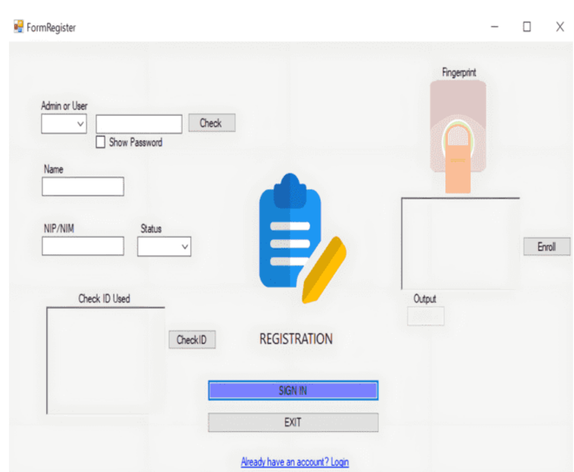

Figure 10. Form Register.

Figure 10 shows registration form is used for new user enrollment. Users are required to enter their personal details and register their fingerprint to ensure secure access to the system. This authentication method prevents unauthorized use.

Figure 11. Login ID.

Figure 11 is the login designed for user authentication. It requires users to enter their credentials and verify their fingerprint before accessing the system. This ensures that only authorized users can operate the system and manage its functions securely.

H. Stepper motor calculations

Micro stepping has been widely used for improved resolution and significantly increased motion stability [11]. The main problem of stepping motor in precision positioning application is that each step angle of stepping motor is quite large, approximately 1/200 of a revolution or 1.8 degrees [12]. Belt Pitch is the distance between the teeth on the belt, which is usually 2 mm for GT2 types, while Pulley Teeth indicates the number of teeth on the pulley which determines the distance traveled per one revolution of the motor. In permanent-magnet and hybrid constructions, when no voltage is applied to the stator coils, the number of magnetically stable shaft position is defined by the ratio of the shaft magnetic pole pairs to the number of pole pairs of stator windings [13]. This formula plays an important role in the calibration and performance optimization of precision drive systems, as it allows adjustment between resolution, speed, and application-specific needs. Step per mm was determined by:

$$Steps(mm) = \frac{(Step\ Revolution) \times (Driver\ Step)}{(Belt\ Pitch) \times (Pulley\ Teeth)} \quad (1)$$

The utilization of the "Steps per mm" formula in belt and pulley-based drive systems provides an important foundation for the calibration and performance optimization process of CNC machines, 3D printers, and other automation devices. By considering the parameters of Step Revolution, Driver Step, Belt Pitch, and Pulley Teeth, this calculation ensures that every linear movement is in line with the software instructions, thus improving the precision and reliability of the system [14].

In addition, selecting the right Steps per mm value allows users to balance the need for high motion resolution with the demands of operating speed, according to the characteristics and objectives of each application.

III. RESULT AND DISCUSSION

A. Photoelectric Sensor Testing

Photoelectric Sensor (E18-D80NK) testing was conducted to evaluate the sensor's performance in detecting objects at various predetermined distances. This test is important to understand the accuracy, consistency, and reliability of the sensor under certain conditions. The test was conducted by varying the distance between the sensor and the object and recording whether the sensor successfully detected the object in each test.

TABLE I
PHOTOELECTRIC SENSOR TEST RESULT

Object Distance (Cm)	Result
2	Success
4	Success
6	Success
7	Success
9	Success
10	Success
12	Failed
14	Failed

Based on the test results, the sensor can detect objects well up to a maximum distance of 10 cm, while at more than 10 cm, the sensor fails to detect. Out of a total of eight tests, six were successful and two failed, resulting in a success rate of 75%. This shows that the sensor has a reliable performance within a certain range but has limitations in detecting objects at longer distances. Therefore, this sensor is more suitable for applications that require detection at short distances, while detection at longer distances requires a sensor with higher specifications or sensitivity adjustments.

B. Stepper Movement

We can calculate the displacement distance of the stepper motor using the previous formula (1), which has the following specifications:

- *Steps per Revolution = 200*
- *Driver Step = 1 (full step)*
- *Belt Pitch = 2 mm*
- *Pulley Number of Teeth = 20*

$$Steps(mm) = \frac{(200)\times(1)}{(2)\times(20)} = \frac{200}{40} = 5 \text{ Steps/mm} \quad (2)$$

This means that the motor must take 5 steps for every 1 mm of linear movement. This analytical approach provides a solid basis for understanding the interactions between mechanical parameters to achieve optimal motion resolution and contribute to the design optimization and calibration of precision drive systems.

$$Error(\%) = \left| \frac{Act.Distance \times Tar.Distance}{Target\ Distance} \right| \times 100\% \quad (3)$$

Note: - Act Distance = Actual Distance
- Tar Distance = Target Distance

To assess the system's precision, movement tests were conducted on the X, Y, and Z axes, with results summarized in Tables 2, 3, and 4.

TABLE II
X AXIS MOVEMENT TESTING

Target Distance(mm)	Actual Distance(mm)	Error%
45	45	0
100	99	0
150	149	0,6
200	199	0,5
250	252	0,8
300	298	0,6
350	347	0,8
400	402	0,5
450	452	0,4
500	505	1
Mean Error (%)		0,52

TABLE III
Y AXIS MOVEMENT TESTING

Target Distance(mm)	Actual Distance(mm)	Error%
20	20	0
50	50	0
115	114	0,8
214	213	0,5
279	278	0,4
290	289	0,3
330	332	0,6
370	373	0,8
384	388	1
448	455	1,5
Mean Error (%)		0,59

TABLE IV
Z AXIS MOVEMENT TESTING

Target Distance(mm)	Actual Distance(mm)	Error%
150	150	0
150	150	0
150	150	0
150	150	0
150	151	0,6
150	151	0,6
150	149	0,6
150	150	0
150	150	0
150	149	0,6
Mean Error (%)		0,24

The experimental analysis demonstrates that the stepper motor system maintains a high level of precision, with mean errors below 1% across all axes. However, the X and Y axes exhibit slightly higher errors than the Z axis, suggesting potential influences from belt tension, mechanical play, or external forces. Further refinement in system calibration and alignment could enhance accuracy, particularly in horizontal displacement.

C. *X & Y Time Testing*

This test aims to evaluate the travel time of the stepper motor in the X and Y axes based on the distance traveled. This data is important to understand the efficiency of the system's movement, the speed difference between axes, and the potential optimization of movement control algorithms in stepper motor-based systems.

TABLE V
X & Y AXIS TIME TESTING

X & Y distance (mm)	X TIME (S)	Y Time (s)	X + Y Time (s)
(296,448)	2,66	2,94	5,6
(446,448)	3,15	2,94	6,09
(296,382)	2,66	2,86	5,52
(446,382)	3,15	2,86	6,01
(296,279)	2,66	2,22	4,88
(446,279)	3,15	2,22	5,37
(296,214)	2,66	1,60	4,26
(446,214)	3,15	1,60	4,75
(296,115)	2,66	1,34	4
(446,115)	3,15	1,34	4,49

D. *X and Y Synchronization Time Testing*

TABLE VI
X, Y SYNCHRONIZATION TIME TESTING

X + Y Time (s)	XY SYNCHRONIZATION (S)	DIFFERENCE TIME (S)
5,6	3,19	2,41
6,09	3,70	2,39
5,52	3,10	2,42
6,01	3,25	2,76
4,88	2,41	2,47
5,37	2,91	2,46
4,26	2,25	2,01
4,75	2,72	2,03
4	2,20	1,8
4,49	2,56	1,93

Table 6 shows the results of time testing after synchronizing the movement of the X and Y axes. The difference between the total time (X + Y Time) before synchronization and the time after synchronization (XY Synchronization) shows significant efficiency in the movement of the system.

The movement time after synchronization was significantly reduced compared to the total time before synchronization. The average time difference (Difference Time) ranged from 1.93 to 2,76 seconds. Before synchronization, the motor had to complete the movement of the X and Y axes separately, resulting in a longer total time. With synchronization, both axes move simultaneously, resulting in a shorter time required.

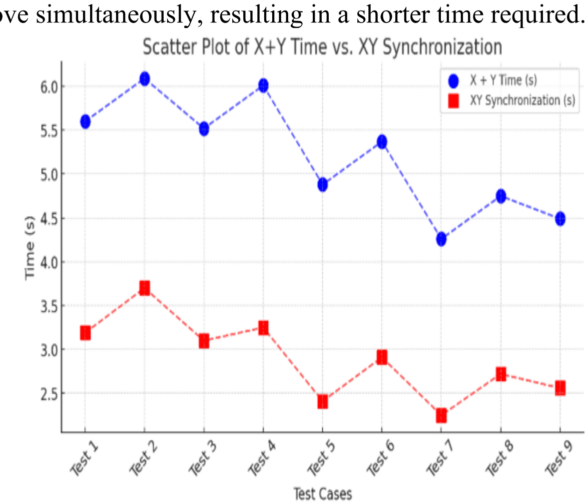

Figure 12. Comparison X Y Axis.

The scatter plot above compares X+Y Time (before synchronization) and XY Synchronization (after synchronization) for each trial. X+Y Time (Blue) is always higher than XY Synchronization (Red). After synchronization, the time required is lower, with a relatively stable pattern. This shows that the synchronization algorithm works well for various movement scenarios.

E. User Interface Blackbox Testing

Black-box testing is conducted to test the functionality of the system based on the inputs and outputs produced, without considering the internal structure or source code [15].This testing aims to ensure that each feature in the system functions according to the specified requirements. The following table presents the test results of various main features of the system based on the designed scenarios, considering the validity of the input and the responses provided by the system.

TABLE VII
BLACKBOX TESTING

Feature Being Tested	Expected Result	Test Result
Register	a. Registration is successful and the system moves to the Login page. b. Registration failed and the system remains on the Register page.	Successful
Login	a. Login failed; the system stays on the Login page. b. Login successful, the system moves to the Menu page.	Successful
Main Menu	All options display correctly and each directs to the appropriate page/function.	Successful
Borrowing	If the input data is complete and valid, the borrowing transaction is successful and recorded; if it is incomplete, the transaction is canceled.	Successful
Retrieval	If the data is valid and registered, the return is successful with the device status updated and the transaction recorded; if not, the return fails.	Successful
History Report (Admin Only)	Admin can see the complete list of transaction history, while users cannot access the report page.	Successful

F. Borrowing Time Testing

The test results of the VB.Net-based lending system show that the processing time is different between users with admin and user status. Of the 10 trials conducted, Admin has a shorter borrowing time (47-50 seconds) than User (55-70 seconds). This difference may be due to access rights, the number of steps in the loan process, and the ease of the interface. This finding shows that user status affects the efficiency of the system, so further analysis is needed to optimize the lending flow, especially in the aspects of data validation, user interface, and security procedures, so that the system can operate more efficiently and consistently.

TABLE VIII
BORROWING TIME TESTING

Name	Status	Time(s)
Naufal	Admin	47
Juan	Admin	50
Gunawan	User	65
Danu	User	61
Akbar	User	59
Martinus	User	55
Andra	User	70
Maulana	User	66
Bagus	User	69
Wendi	User	56

G. Retrieval Time Testing

The results of the system testing show a difference in the return process time between users with Admin and User status. From the 10 trials conducted using a VB.Net-based interface, Admin completed the process faster (42–45 seconds) compared to User (52–62 seconds). This difference may be caused by factors such as access rights, the number of steps in the return procedure, and the ease of the provided interface. A longer time range for the User indicates that the return process can still be optimized to improve efficiency, for example, by simplifying procedures or enhancing system responsiveness. These results serve as a basis for further evaluation to ensure that the return system operates faster, more efficiently, and consistently for all users.

TABLE IX
RETRIEVAL TIME TESTING

Name	Status	Time(s)
Naufal	Admin	42
Juan	Admin	45
Gunawan	User	58
Danu	User	60
Akbar	User	52
Martinus	User	57
Andra	User	58
Maulana	User	60
Bagus	User	62
Wendi	User	55

IV. CONCLUSION

This research demonstrates the design and effective implementation of a laboratory component loan and return management system that integrates key microcontrollers, including Arduino Uno, ESP32, and Raspberry Pi 3, with a VB.NET based application, equipped with an ESP32 communication module, database, and fingerprint identification system. Tests and analyses revealed that although the main components-such as the proximity sensor, stepper motors on the X, Y, and Z axes, and the fingerprint module-were well integrated, with the sensor achieving a 75% success rate at a distance of 10 cm and the motors recording an average error of less than 1%, there were still minor calibration inconsistencies between the horizontal and vertical axes, as well as differences in loan and return times between the Admin and User roles. These results underline the accuracy and increased security provided by the system; however, they also highlight limitations in the synchronization of axis movements and the need for optimization in user access procedures. Therefore, further research should aim to refine the calibration process, improve the process flow to ensure an efficient and uniform user experience, and explore the continued integration of biometric and sensor technologies to improve the overall performance and security of the system.

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