Design and Development of Centralized Anti-Theft Motorcycle System

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ABSTRACT

Motorcycle theft remains one of the most prevalent property crimes in Malaysia, driven by factors such as high demand for spare parts, ease of mobility, and insufficient physical security in public parking areas. To address this issue, this paper presents the design and development of a centralized anti-theft motorcycle system that integrates smart surveillance, mobile-based user authentication, and automated locking mechanisms. The proposed system utilizes a modular architecture comprising a robotic gripper, ultrasonic sensors, and an ESP-32 microcontroller, all coordinated via a secure web-based mobile application. Users can remotely manage their motorcycle's security status through QR code verification, while real-time monitoring and passive surveillance enhance situational awareness and deterrence. A lab-scale prototype was developed to validate the system's functionality, demonstrating its potential to significantly reduce theft incidents in shared parking environments. This work contributes to the advancement of smart mobility infrastructure and offers a scalable solution for urban safety enhancement.

Keywords— Anti-theft system, centralized parking, IoT surveillance, motorcycle theft, smart mobility.

INTRODUCTION

In Malaysia, there are approximately 12 million motorcycles registered with the Road Transport Department (RTD) [1], which is a significant number when compared to the country's population of around 34 million [2]. Motorcycles are commonly chosen as the primary mode of transport because they're affordable, fuel-efficient, and practical especially for short trips in urban and suburban areas [3], [4]. Moreover, the lack of reliable public transportation options often pushes lower-income households and rural communities to rely on motorcycles [5]. Their flexibility and ability to save time in heavy traffic also make them a popular choice for daily commuting [5].

Despite being the main form of transportation for many Malaysians, motorcycle theft remains one of the most widespread property crimes. Between 2018 and 2023, over 92,000 cases were reported, making up 73.7% of all property-related crimes according to the Royal Malaysia Police (PDRM) [6]. Research by Ahmad et al. found that urban areas like Petaling Jaya and Sepang had the highest theft rates, largely due to high population density and inadequate vehicle security infrastructure [7]. In Alor Setar, GIS-based hotspot mapping revealed that residential and commercial zones are particularly vulnerable, underscoring the urgent need for centralized and secure motorcycle parking systems [8].

Motorcycle theft tends to be concentrated in suburban areas, where facilities like bus stops and shops create opportunities for offenders to target parked vehicles. Socioeconomic factors also play a role—areas with a high number of low-income residents and domestic migrants are more prone to theft, suggesting that economic hardship and residential instability are major contributors. Interestingly, the presence of surveillance cameras was found to correlate positively with theft incidents. This may be because such areas attract more motorcycles, inadvertently increasing the chances of theft rather than deterring it [9]. Studies also show that peer influence is a key factor among youth offenders, especially when family and school support systems are weak [10]. Many of these crimes are committed in groups, with 80% of teenage offenders aged 15–18 admitting they were influenced by friends with similar backgrounds [11]. These insights highlight the pressing need for a system that can effectively reduce the risk of motorcycle theft.

The centralized anti-theft motorcycle system

Public motorcycle parking areas in Malaysia are increasingly exposed to theft due to the absence of effective surveillance and centralized control systems. These open and often unsupervised environments provide easy opportunities for offenders to target parked motorcycles, especially in high-density urban zones. According to IEEE Public Safety Technology, parking lots are particularly vulnerable to crimes like theft and vandalism, and basic CCTV systems alone are often insufficient to deter such incidents [12].

While various standalone anti-theft devices exist, they are typically limited in scope and rely heavily on individual user vigilance. This fragmented approach has proven ineffective in shared environments where multiple motorcycles are parked without coordinated security measures. Recent advancements in smart surveillance systems, including edge computing and AI-based monitoring, have shown promise in improving detection accuracy and real-time response in public parking scenarios [13], [14].

Moreover, a bibliometric analysis by W.Q Fan et al. highlights the growing role of artificial intelligence in smart city surveillance systems, emphasizing the need for ethical and robust governance framework to ensure public thrust and effectiveness [15]. These insights reinforce the importance of integrating intelligent technologies into urban safety infrastructure.

To address these limitations, a centralized anti-theft motorcycle system is proposed. This system integrates digital control, real-time monitoring, and physical locking mechanisms into unified architecture. Through a mobile application, users can remotely manage the security status of their motorcycles, while a centralized database ensures coordinated control and logging of all activities.

The system is designed not only to enhance individual vehicle protection but also to support broader crime prevention strategies in public parking facilities. By combining smart infrastructure with user-friendly interfaces, the proposed solution aims to reduce theft incidents and improve overall safety for motorcycle owners.

System Design and Architecture

The block diagram of the proposed system is as shown in Fig. 1. The centralized anti-theft motorcycle system is developed with a focus on enhancing security, scalability, and user accessibility in shared parking environments. The architecture is modular, allowing each component to perform a distinct role while maintaining seamless integration across the system.

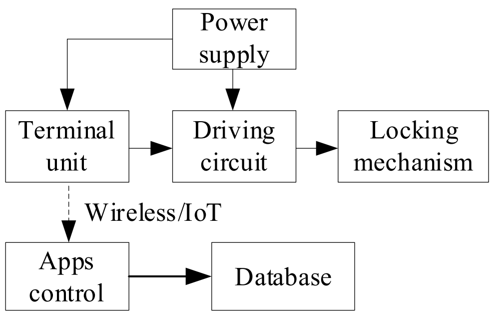


Fig. 1. Block diagram of the system.

At the core of the system lies the apps control databases, which not only stores user credentials and motorcycle status but also acts as the decision-making centre. This centralized control enables real-time monitoring and remote access, allowing users to interact with the system through a mobile application. The app interface is designed to be intuitive, enabling users to lock or unlock their motorcycles, receive alerts, and track activity with minimal effort.

Once authenticated, a secure command is transmitted to the terminal unit installed at the parking site. This unit processes the command and activates the driving circuit, which in turn engages the locking mechanism to physically secure the motorcycle. The entire process is completed within seconds, and the user receives a confirmation notification on their device.

In the event of unauthorized access or tampering, the system immediately triggers an alert. The database logs the incident, and the user is notified via the app. This real-time response mechanism ensures that any suspicious activity is promptly addressed, reducing the likelihood of theft.

The terminal unit serves as the physical interface between the digital commands and the motorcycle's security hardware. It receives encrypted instructions from the database and processes them through the driving circuit, which is responsible for activating the Locking Mechanism. This mechanism is engineered to physically secure the motorcycle, preventing unauthorized movement or tampering.

The system also supports remote unlocking, allowing users to disengage the lock when they return. All interactions are recorded in the database for audit and analysis purposes. This workflow not only enhances user convenience but also strengthens the overall security framework of public motorcycle parking facilities.

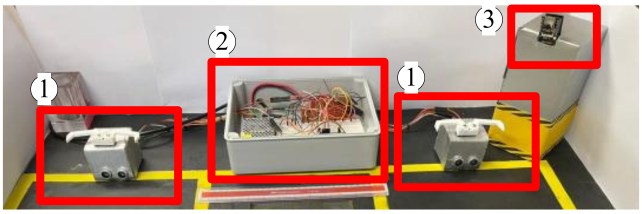
What sets this system apart is its centralized architecture, which allows for coordinated control of multiple motorcycles within a single parking facility. This design not only simplifies management but also include integration with surveillance systems, RFID-based access control etc. By combining digital intelligence with robust physical security, the system offers a practical and scalable solution to address the growing concern of motorcycle theft.

SYSTEM DESIGN AND ARCHITECTURE

As the prove of concept for the system, a lab scale prototype was design and developed. A lab-scale prototype is essential to demonstrate the practical feasibility of a proposed concept before full-scale development. It allows the core functionalities tested, identify design flaws, and optimize performance in a controlled environment. For this research, the prototype helps simulate detection and control mechanisms, ensuring the system works effectively before being implemented in actual parking areas.

There are four major components in the system which are; locking mechanism, terminal unit, apps control for user identification and passive surveillance system to continuously monitor the surrounding environment and provide recorded the event of a theft or suspicious activity.

The hardware prototype of the system is as shown in Fig. 2. Meanwhile, apps that control the system were installed on a mobile phone. The architecture of the apps control will be explained in later sub chapter. On this prototype, two parkings were developed to test it functionality to cater more than one user. The functionality for each component and planning toward actual system implementation will be discussed in the next sub chapter.



1 : Locking mechanism
2 : Terminal unit
3 : Passive surveillance system

Fig. 2. Hardware of the system.

Locking Mechanism

The component that playing role to ensure to keep the motorcycle in safe position is the locking mechanism. A

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robot gripper drive by a stepper motor were used to construct the locking mechanism. Detail of the construction is as shown in Figure 3.

The robot gripper is used to securely lock the front tyre of a motorcycle. The motion of the robot gripper to lock and unlock is drive by the stepper motor. To enhance the reliability of the locking mechanism, an ultrasonic sensor is integrated to detect the presence of a motorcycle. Locking mechanism, is only activated when the sensor confirms that a motorcycle is properly positioned. This precautionary feature prevents accidental or unnecessary locking, thereby ensuring operational safety.

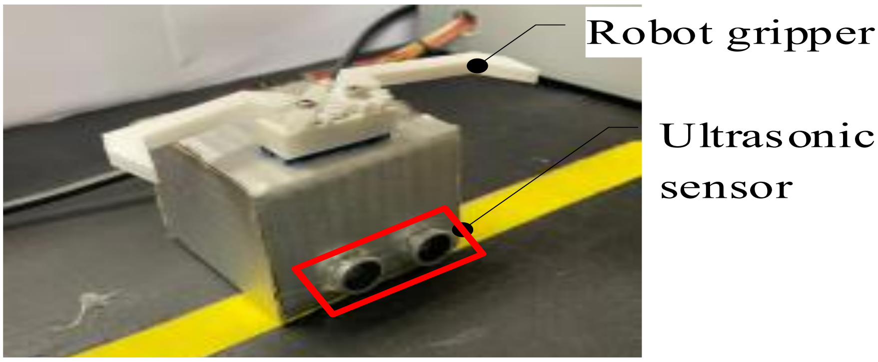

Fig. 3. Prototype of the locking mechanism.

The operation flow of locking mechanism is as shown in Figs. 4 and 5 respectively. Initially, an ultrasonic sensor detects the presence of a motorcycle tire. Once the presence is confirmed, the system awaits a locking instruction from the terminal unit. Upon receiving this command, the robotic gripper that driven by a stepper motor moves into the locked position to secure the motorcycle tire. Unlocking, however, is only permitted after successful user identification, ensuring that only authorized users can release the lock. This sequence not only prevents accidental locking but also enhances the overall security and user trust in the system. Then, the locking mechanism is revert into idle position while waiting the next cycle of it operation.

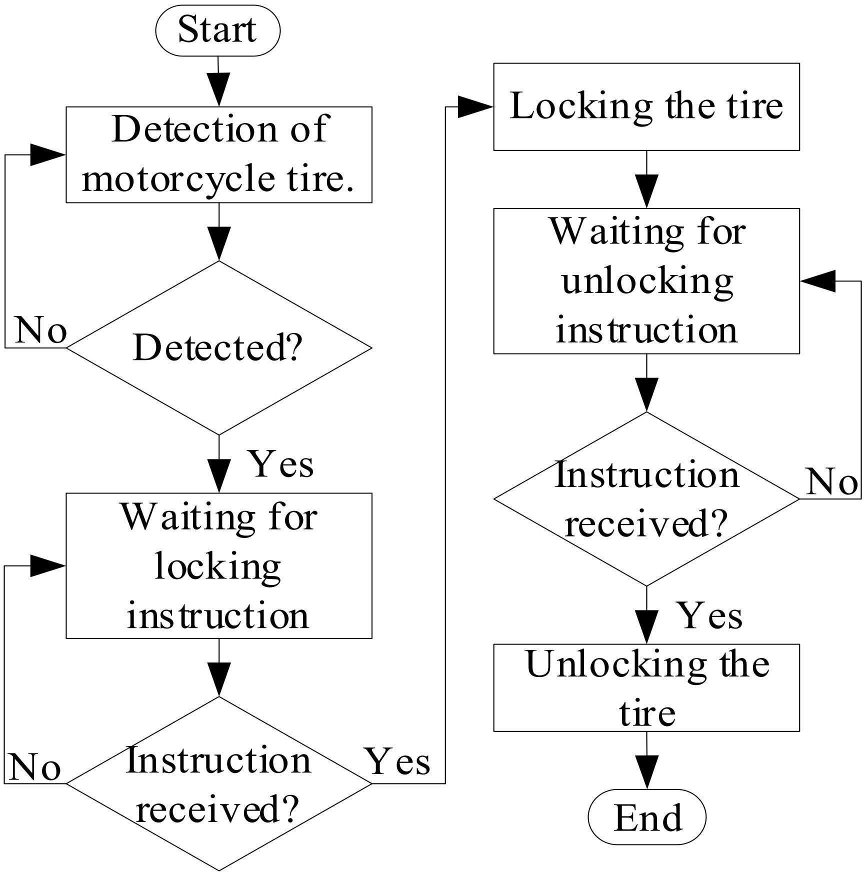

Fig. 4. Operation flow of the locking mechanism.

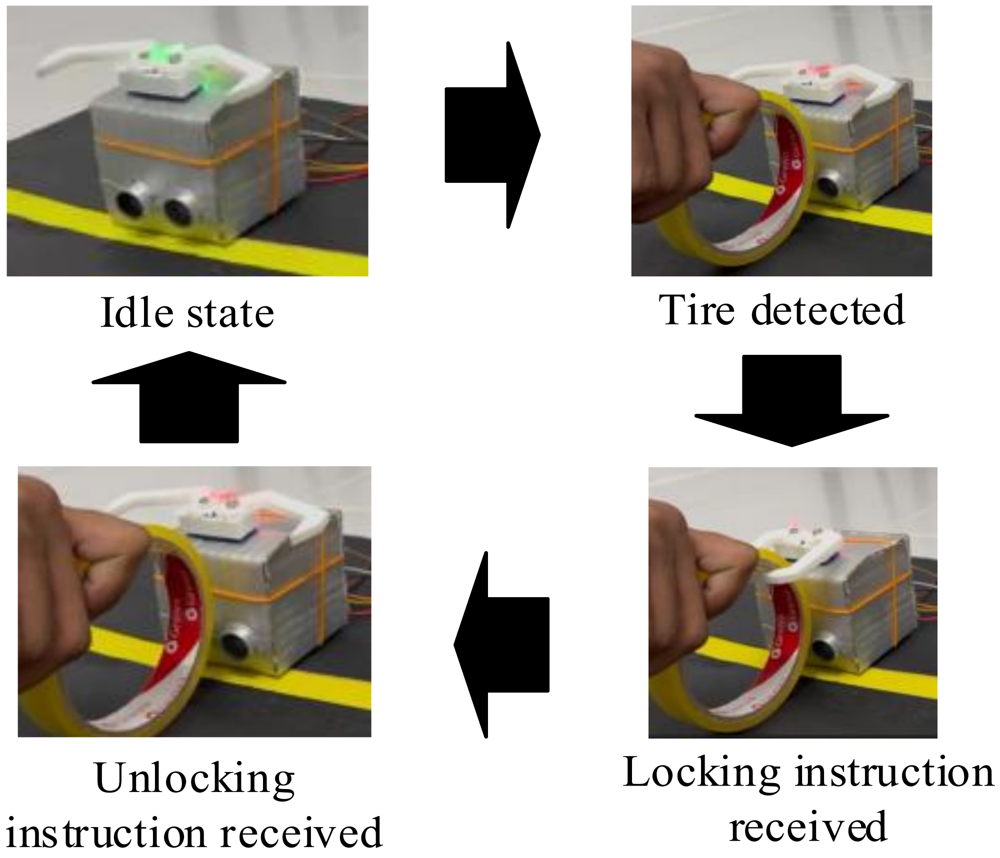

Fig. 5. Operation flow of the locking mechanism.

While the prototype utilizes a stepper motor and robotic gripper for proof-of-concept, the proposed real-world implementation involves a more robust electromechanical clamping system. This system may incorporate a brushless DC motor with positional feedback, reinforced locking arms, and dual-sensor verification to ensure accurate tire detection. Table 1 shows the comparison between the prototype and proposed real system.

Terminal Unit

The ESP-32 was selected as the core processing unit due to its integrated Wi-Fi and Bluetooth capabilities, enabling seamless communication with the mobile application for QR code-based user authentication. Its dual-core architecture supports concurrent tasks such as ultrasonic sensor monitoring and motor control. Communication between the app and ESP-32 is secured via HTTPS, ensuring data integrity during lock/unlock operations. Additionally, the system incorporates error handling mechanisms to manage sensor failures or network disruptions, and a manual override option is provided for fail-safe operation. Figs. 6 and 7 depicted the terminal unit of the prototype and its architecture respectively.

TABLE 1 Comparison between prototype and proposed real system for the locking mechanism.

Component	Prototype	Real Implementation
Locking Mechanism.	Robot gripper with basic mechanical lock.	Electromechanical clamp with reinforced locking arms.
Motor Type.	Stepper motor.	Brushless DC motor with positional feedback.
Sensors Used.	Ultrasonic sensor for tire presence detection.	Dual-sensor system (Ultrasonic + IR or pressure sensor).
Safety Features.	Lock only activates when motorcycle is detected.	User authentication required before unlocking; tamper detection; fail-safe mechanism.

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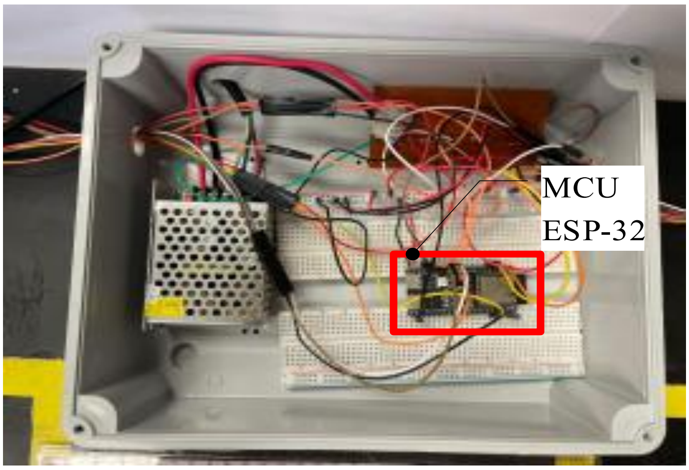

Fig. 6. Prototype of the terminal unit.

The ESP-32 is interfaced with an ultrasonic sensor to detect the presence of a motorcycle tire within the designated parking slot. Upon detection, the system remains in standby mode until a lock command is issued by the user through the mobile app. Once activated, the ESP-32 sends a signal to the stepper motor to engage the robotic gripper and secure the tire. On this stage of operation, the signal to lock the motorcycle will be send according to the ultra sonic sensor and stepper motor within the same group. For example, the signal from ultra sonic sensor 1 is dedicated to activate the stepper motor 1 for parking space 1. Similarly, the unlocking process is initiated only after successful user authentication via QR code scanning in the mobile application, upon which the ESP-32 transmits an unlock signal to the stepper motor. This architecture ensures secure, wireless control and efficient operation of the locking mechanism.

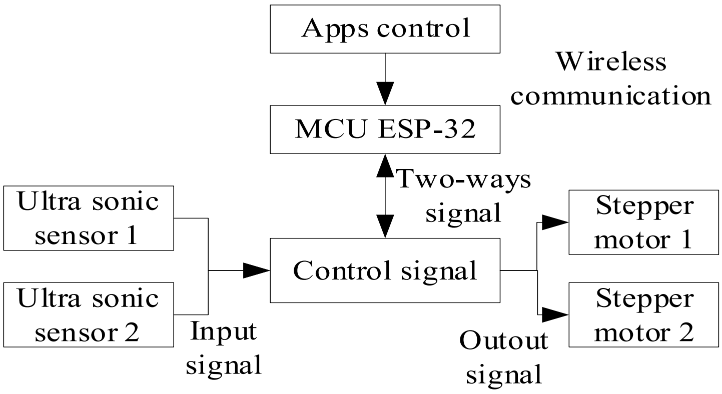

Fig. 7. Architecture of the terminal unit.

For real-world implementation, the terminal unit should incorporate an industrial-grade microcontroller or maintain the ESP-32 platform with enhanced reliability features such as external watchdog timers and secure communication protocols. Additional modules like LTE connectivity can be integrated for areas with limited Wi-Fi coverage. The motor control system should employ drivers with positional feedback to ensure precise locking and unlocking operations. Furthermore, encrypted QR codes and HTTPS communication will safeguard user authentication, while cloud integration will enable remote monitoring and scalability. Table 2 listed the comparison between the prototype and proposed of the terminal unit for real implementation.

TABLE 2 Comparison between prototype and proposed real system for the terminal unit.

Component	**Prototype**	**Real Implementation**
MCU Type	ESP-32 (basic version)	ESP-32 WROOM/WROVER or STM32/Raspberry Pi (industrial-grade)
Communication Method	Wi-Fi only	Wi-Fi + LTE (optional backup)
Motor Control	Stepper motor with basic driver	BLDC with driver and positional feedback

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	without feedback	
Security Features	QR code via mobile app; basic HTTPS communication	Encrypted QR code; secure HTTPS/TLS; fail-safe override
Scalability	Limited to local control; no cloud integration	Cloud integration; remote monitoring; admin dashboard

APPS CONTROL

The adoption of a web-based mobile application offers significant advantages for user interaction and system scalability. Unlike native applications, web-based solutions provide cross-platform compatibility, eliminating the need for installation and ensuring accessibility from any device with a browser. Real-time updates on parking availability are achieved through direct communication with the ESP-32 microcontroller, while secure authentication is enforced via encrypted QR codes and HTTPS protocols. Furthermore, centralized updates simplify maintenance, and the architecture supports future integration with cloud services for analytics and payment systems, enhancing both user convenience and operational efficiency.

Users begin by scanning a QR code, which launches a secure web-based application. This application communicates with the ESP-32 microcontroller to retrieve real-time information on available parking spaces. Once the user parks in an empty slot and the ultrasonic sensor confirms the presence of the motorcycle, the corresponding parking space icon on the app is activated. The user can then select this icon and proceed to enter their credentials for authentication. Only after successful verification is the locking mechanism enabled, allowing the robotic gripper to secure the motorcycle tire. This interactive process simplifies user engagement, enhances security, and ensures that locking operations are performed only by authorized individuals. This sequence of operation of the web-based apps control is as shown in Figure 8.

To further enhance user confidence and system transparency, the web-based application integrates with a passive surveillance system. This feature allows users to view real-time visual feedback of their parked motorcycle directly through the application, providing an added layer of security and peace of mind. Additionally, the application maintains a comprehensive usage log to record operational activities such as lock and unlock events, parking slot selection, and system interactions. Importantly, no user credentials are stored within the system, ensuring privacy and compliance with data protection principles. This approach balances functionality with security, offering users convenience without compromising personal data integrity.

The proposed architecture and features are sufficient for a functional prototype and can be extended for real-world deployment with additional measures for security, scalability, and reliability. Enhancements such as encrypted communication, token-based QR authentication, cloud integration, and fail-safe mechanisms will ensure the system operates securely and efficiently in practical environments.

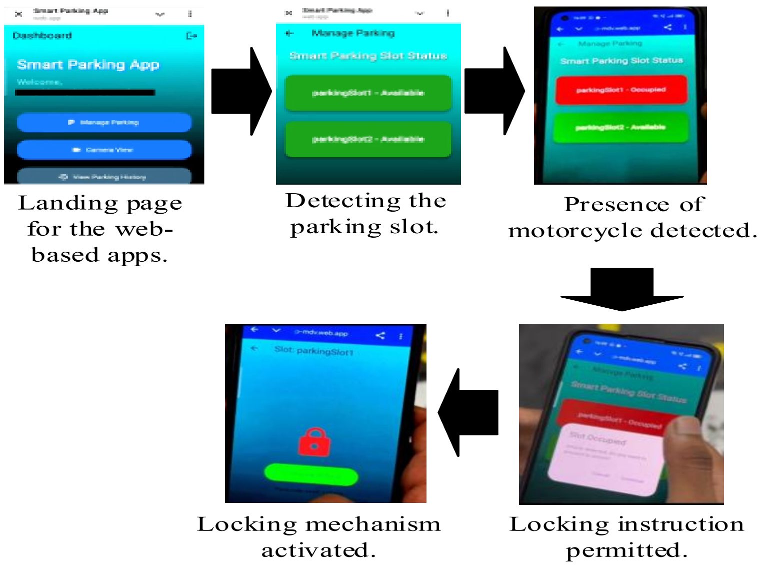

Fig. 8. The flow of web-based apps control.

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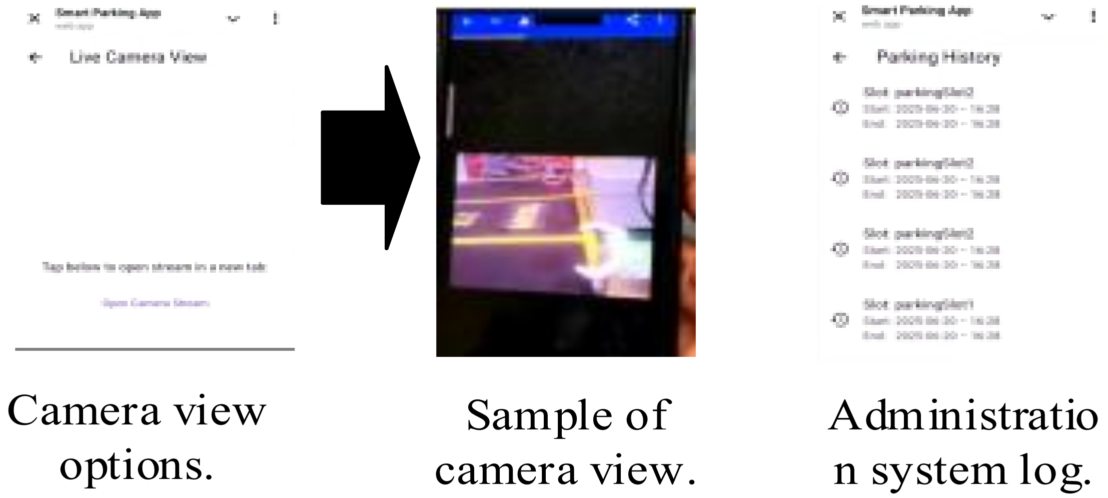

Fig. 9. Additional feature of web-based apps control.

PASSIVE SURVEILLANCE SYSTEM

To strengthen security and provide visual evidence in case of theft or unauthorized access, the system incorporates a passive surveillance feature. This subsystem utilizes an ESP-32 camera module, chosen for its seamless compatibility with the ESP-32 microcontroller and built-in wireless communication capabilities. The camera continuously records footage of the parking area, storing video streams in a dedicated surveillance repository for future reference. Figure 10 shows the camera used in this prototype.

In addition to passive recording, the web-based application offers users real-time monitoring of their parked motorcycle through an integrated video feed. This feature enhances user confidence by allowing remote visual verification without requiring additional hardware or complex setup. By combining passive surveillance with user-accessible monitoring, the system delivers a balanced approach to security—providing deterrence against theft while maintaining user convenience and trust.

To strengthen security and provide visual evidence in case of theft or unauthorized access, the system incorporates a passive surveillance feature. The prototype utilizes an ESP-32 camera module for simplicity and seamless integration with the ESP-32 microcontroller. However, for real-world deployment, the surveillance system should adopt high-resolution IP cameras (minimum 1080p or 2MP) to ensure clear identification of vehicles and individuals, in line with IEC/EN 62676 recommendations for pixel density.

Fig. 10. Passive surveillance system using ESP-32 camera.

Recorded footage must be stored securely in a dedicated repository or cloud storage with encryption, and having certain retention period such as within 30 to 90 days for general premises and up to 180 days for government office buildings as specified in the guidelines typically in Malaysia perspective. Motion detection and timestamped logs should be implemented to optimize storage and provide reliable evidence. Table 3 shows comparison between prototype and proposed real system for the passive surveillance system.

TABLE 3 Comparison between prototype and proposed real system for the passive surveillance system.

Component	Prototype	Real Implementation
Camera Type	ESP-32 Camera Module	IP Camera (CCTV) with network capability
Resolution	Low resolution (VGA ~640x480)	Minimum 1080p (2MP) or higher (up to 4K)
Storage Method	Local storage (SD card or internal buffer)	Secure cloud storage or NVR with RAID
Retention Period	Short-term (temporary or session-based)	30 to 180 days
Integration Features	Basic integration with ESP-32 MCU and web app	Encrypted real-time streaming, motion detection, cloud logging, user-accessible via web app

CONCLUSION

The design and development of a prototype for the centralized anti-theft motorcycle parking system have been discussed. The components of the system are including locking mechanism, terminal unit, apps control and passive surveillance system. All system components were integrating well by using MCU ESP-32 as its main processor and apps control that communicating with the main processor wirelessly. The locking mechanism are built with ultrasonic sensors for tire detection, and a stepper motor driven robotic gripper for secure locking. Additional features such as passive surveillance integration and activity logging further enhance system security and user confidence. While the prototype provides proof of concept, real-world implementation will require improvements has also covered. Future work will focus on scalability, cloud integration, and advanced security measures to deliver a robust, user-friendly, and secure centralized motorcycle parking solution suitable for practical deployment in government and commercial environments.

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