An Intelligent IoT-Based Virtual Barrier for Smart Museum Collection Protection Using PIR-Ultrasonic Sensor Fusion and ESP32-CAM

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***Abstract*— Open-exhibition museums offer an engaging and immersive visitor experience but also expose valuable collections to a higher risk of physical damage due to unrestricted visitor interaction. This challenge is particularly evident at the Maros-Pangkep Geological Information Center (Pusat Informasi Geologi-PIG), Indonesia, where several prehistoric animal fossil replicas are displayed without physical barriers. Conventional protection methods based on human supervision and warning signs are insufficient to provide continuous real-time monitoring. Therefore, this study proposed an intelligent Internet of Things (IoT)-based virtual barrier system to enhance the protection of open museum collections. The system was developed by integrating a NodeMCU ESP8266 microcontroller, an ESP32-CAM module, Passive Infrared (PIR) and ultrasonic sensors, a stepper motor, multilingual voice warnings (in Indonesian, Bugis-Makassar and English), and an Android-based monitoring application. An AND-based sensor-fusion mechanism was implemented to improve intrusion detection accuracy while minimizing false alarms. Experimental results showed that the PIR sensor effectively detected human motion within a range of 20-120 cm, whereas the HC-SR04 ultrasonic sensor achieved approximately 97% distance measurement accuracy with an error margin of 1-2 cm. The proposed virtual barrier successfully identified intrusion events within a predefined safety boundary of 110 cm, activated an immediate local audible alarm, captured visual evidence using the ESP32-CAM module, and transmitted event information to the Android application with an average end-to-end transmission latency of approximately 2 seconds under adequate network conditions. These results demonstrate that the proposed system provides an effective, and adaptive solution for protecting open-exhibition museum collections while preserving exhibition aesthetics and supporting real-time security monitoring and incident verification.**

Keywords*— *Internet of Things (IoT), Virtual Barrier, Museum Collection Protection, Intrusion Detection, PIR sensor, ultrasonic sensor, ESP32-CAM.

I. INTRODUCTION

Museums and geological interpretation centers play an essential role in preserving geoheritage while promoting public education and conservation awareness. Recent developments in exhibition design have shifted museums toward more interactive and immersive environments, allowing visitors to engage more closely with exhibited objects. Although this approach enhances educational experiences, it also increases the risk of accidental or intentional physical interaction with valuable collections, particularly in open-exhibition areas where conventional physical barriers are intentionally minimized [1], [2].

The Maros-Pangkep Geological Information Center (Pusat Informasi Geologi, PIG), officially inaugurated in April 2021, is a strategic geotourism and educational destination located in Pangkajene and Islands Regency, South Sulawesi, Indonesia. As the fifth Geological Information Center established by the Geological Agency of the Ministry of Energy and Mineral Resources (Badan Geologi Kementerian Energi dan Sumber Daya Mineral-ESDM) of Indonesia, the facility serves a significant national role in disseminating information on the geological heritage of the Maros-Pangkep region to the public. Its primary mission is to enhance public awareness and encourage active participation in the conservation and sustainable preservation of the region's geological heritage [3].

The strategic role of the Maros-Pangkep PIG has been further strengthened by its contribution to supporting the Maros-Pangkep UNESCO Global Geopark. Following the region's designation as a UNESCO Global Geopark in 2023, the management of its geological heritage has been expected to comply with international standards across multiple aspects, including collection management, exhibition design, visitor services, and collection security. Consequently, the Geological Information Center serves not only as the primary educational gateway for communicating the geological significance of the geopark to the public but also as an indicator of the region's readiness to maintain international recognition through sustainable conservation and effective heritage management. In this context, ensuring the preservation and security of museum collections has become a fundamental priority for supporting the long-term sustainability of the geopark [1], [4].

To achieve its educational mission, the Maros–Pangkep PIG adopts a modern exhibition concept organized into four thematic zones: the Geological History of Sulawesi Island, Natural Hazards and Natural Resources, History of Life, and the Maros-Pangkep UNESCO Global Geopark. The facility delivers geological information through a combination of informative graphic panels, immersive karst cave dioramas,

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and interactive multimedia technologies, including touchscreen displays and audiovisual presentation rooms. Within these exhibition areas, most small and fragile collections, such as pottery artifacts, geological rock specimens, shell fossils, and traditional boat miniatures, are securely protected in glass display cases to ensure their long-term preservation while remaining accessible for public education [5].

However, the exhibition approach that constitutes both the primary attraction of the Maros-Pangkep PIG and the main issue addressed in this study is its open-exhibition concept. The flagship collections, such as a full-scale Babirusa skeletal replica and several prehistoric elephant fossil skull replicas, are displayed on elevated sand platforms without physical protective barriers such as glass display cases or safety ropes. While this exhibition design provides visitors with a more immersive educational experience, it also substantially increases the risk of accidental damage resulting from direct physical interaction with the collections, particularly during periods of high visitor attendance. Although visits are organized through a reservation system, the number of visitors in each group varies considerably, ranging from approximately 10 to more than 250 individuals per session, with many groups consisting of school students who actively interact within the exhibition area. Currently, collection protection relies primarily on manual supervision by museum guides and warning signage. Since PIG operates exclusively on a reservation basis and does not maintain dedicated on-site security personnel, the number of guides assigned is adjusted according to the size of each visitor group. For example, groups of fewer than 50 visitors are typically accompanied by one or two guides, whereas larger groups of 150-250 visitors may require five to seven guides. Nevertheless, the disproportionate ratio between guides and visitors makes continuous monitoring of individual behavior around open collections impractical, thereby creating significant security vulnerabilities and increasing the need for an automated monitoring system capable of protecting valuable collections without compromising visitor accessibility or the aesthetic quality of the exhibition environment.

Recent advances in Smart Museum and digital heritage have demonstrated that Internet of Things (IoT) technologies are becoming fundamental components for improving visitor experiences, collection management, and cultural heritage preservation. Reference [6] emphasized that modern museums are evolving toward intelligent digital ecosystems through the integration of sensor networks, embedded systems, machine vision, wireless communications, and digital twins, enabling real-time monitoring and management of museum assets. Similarly, reference [7] proposed a semantic IoT framework for Smart Museums, highlighting that interoperable sensor infrastructures are essential for supporting intelligent services and contextual awareness within cultural heritage environments. While these studies provide comprehensive architectures for smart museums, they primarily focus on digital transformation and information interoperability rather than physical protection of open-exhibition collections.

Several studies have investigated IoT-based security systems for object protection using various sensing technologies. Reference [8] developed an IoT-based monitoring system for protecting the valuable *Batu Bedil* artifact at the Lampung Museum using a Passive Infrared (PIR) sensor integrated with the ThingsBoard platform. The system successfully generated warning notifications when visitors entered a predefined safety distance of 50 cm, demonstrating the feasibility of establishing a virtual protective boundary around museum collections. However, the monitoring mechanism relied on a single PIR sensor with a fixed sensing direction, limiting detection coverage and making the system susceptible to false alarms caused by irrelevant movements. To improve intrusion verification, reference [9] combined PIR and ultrasonic sensors with voice notifications in a prison security system, showing that multi-sensor integration enhanced detection reliability compared with a single-sensor approach. Likewise, reference [10] proposed an IoT-integrated anomaly detection system for agricultural security that provided real-time monitoring and web-based notifications for restricted areas. Although both studies demonstrated the advantages of combining multiple sensors and real-time notification mechanisms, their applications were designed for static surveillance environments and did not address the unique requirements of protecting museum collections, where visitors are encouraged to move freely while maintaining a safe distance from exhibited objects.

The concept of virtual boundaries has also been explored beyond museum applications. Reference [11] introduced an IoT-based virtual fence system for preventing occupational accidents in construction environments by continuously monitoring worker positions relative to hazardous zones. Their results confirmed that virtual boundaries could provide adaptive and non-invasive protection without interrupting normal activities. Nevertheless, the proposed system was intended for occupational safety rather than cultural heritage preservation and did not incorporate close-range object protection, visual evidence acquisition, or visitor-oriented warning mechanisms. Furthermore, recent studies on Smart Museums have mainly emphasized digital transformation, visitor navigation, and information services [6], [7], [8], [12], [13], [14] instead of intelligent physical protection for vulnerable collections.

Based on the reviewed literature, several research gaps remain. First, existing museum protection systems generally employ static sensing configurations with limited monitoring coverage. Second, although multi-sensor approaches have been investigated in other security domains [15], they have not been specifically optimized for protecting open-exhibition museum collections. Third, current virtual boundary systems rarely integrate sensor fusion, dynamic multidirectional scanning, automatic visual documentation, and multilingual warning mechanisms into a unified protection framework. Therefore, this study proposes an intelligent IoT-based virtual barrier that integrates PIR and ultrasonic sensors through AND-based sensor-fusion logic, a stepper motor for dynamic scanning, ESP32-CAM for automatic visual documentation, multilingual voice warnings, and a mobile-based activity log. Unlike previous studies, the proposed system not only improves intrusion detection accuracy and minimizes false alarms but also provides comprehensive evidence recording and remote monitoring capabilities while preserving visitor comfort and the aesthetic value of open museum exhibitions.

II. METHOD

A. System Architecture Design

Fig 1 illustrates the operational workflow of the virtual barrier system, which dynamically protects museum collections by integrating a Passive Infrared (PIR) sensor and an ultrasonic distance sensor mounted on a stepper motor to perform continuous left-right scanning. In this architecture, the PIR sensor functions as the primary motion detector, while the ultrasonic sensor serves as a secondary validation sensor. Distance measurements obtained from the ultrasonic sensor are processed only after the PIR sensor has detected motion (HIGH state). Without this initial trigger, ultrasonic sensor readings are ignored and cannot initiate any security response. Once an intrusion is simultaneously confirmed through both motion detection and distance validation within the predefined intrusion zone, the NodeMCU ESP8266 microcontroller immediately activates an audible alarm and instructs the ESP32-CAM module to capture an image of the event. The warning information, together with the captured visual evidence, is subsequently transmitted in real time to the museum administrator's mobile application for monitoring and incident verification.

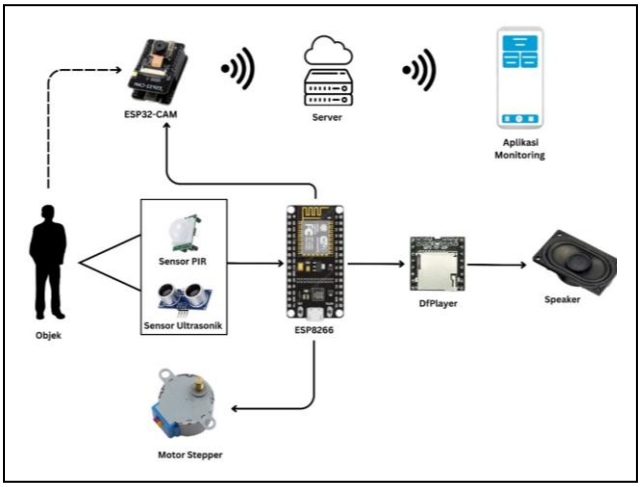


Fig. 1. The workflow of the virtual barrier system.

B. Block Diagram System

Fig. 2 presents the block diagram of the proposed virtual barrier system, which consists of three main components: input, processing, and output. The system was designed to automatically detect unauthorized intrusion into the protected museum collection area, trigger an immediate warning, and transmit visual evidence to the monitoring application for real-time supervision and incident verification.

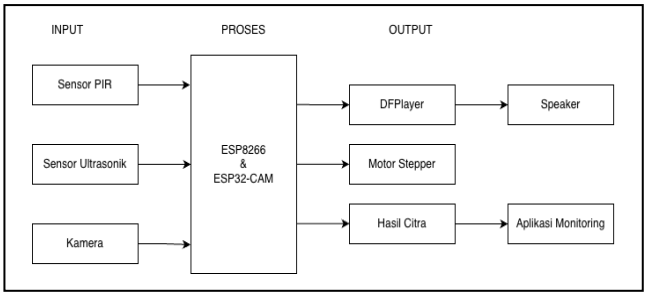


Fig. 2. The block diagram of the virtual barrier system.

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The input layer is responsible for sensing and acquiring environmental information from the area surrounding the protected museum collection. It consists of three primary components:

- The Passive Infrared (PIR) sensor. This sensor detects human presence or motion by sensing changes in the passive infrared radiation naturally emitted by the human body.
- The ultrasonic sensor for measuring the distance between an approaching object and the protected collection. It is used to determine whether the object has entered or crossed the predefined safety zone.
- Camera module for capturing visual images of the intrusion event, providing photographic evidence for documentation and subsequent incident verification whenever an intrusion is detected.

At the processing layer, the system integrates the ESP8266 and ESP32-CAM modules to process data acquired from all sensing components:

- ESP8266: The ESP8266 functions as the primary controller, processing data received from the PIR sensor and the ultrasonic sensor. The sensor data are analyzed using an intrusion detection algorithm to determine whether an intrusion has occurred. In addition, the ESP8266 controls the stepper motor to perform continuous dynamic scanning of the protected area.
- ESP32-CAM: The ESP32-CAM is responsible for processing data captured by the onboard camera module. Once an intrusion is confirmed, the ESP32-CAM automatically captures an image of the detected object, compresses the image in JPEG format, and prepares the data for transmission to the monitoring system.

The Output layer represents the system's responses after the intrusion detection process has been completed. The outputs generated by the system include the following:

- DFPlayer and Speaker. The DFPlayer Mini is connected to a speaker to automatically generate an audible alarm or warning message whenever the system detects an intrusion or a violation of the predefined safety boundary.
- Stepper Motor**.** The stepper motor functions as the driving mechanism that rotates the sensor platform, enabling continuous multidirectional scanning of the protected area.
- Visual Evidence in the Monitoring Application. The images captured by the ESP32-CAM module are transmitted to the monitoring application, allowing authorized users to view real-time visual evidence of the intrusion together with the corresponding event timestamp for monitoring and incident verification.

C. Classification of Detection Distance Zone

The detection distance parameters were determined based on the minimum safe distance between visitors and the exhibition object, namely the Babirusa skeletal replica. The proposed system was designed to continuously monitor the protected area using a predefined detection radius, where a

distance of 110 cm or less from the sensing unit was defined as the intrusion threshold. Accordingly, the ultrasonic sensor measurements were classified into two distance zones to determine the appropriate system response.

- Intrusion Zone (1-110 cm): This zone represents the primary protection area defined by the virtual barrier. Visitors detected within this distance are considered to be too close to the collection and may unintentionally touch or damage the exhibited object. When the Passive Infrared (PIR) sensor first detects motion and the ultrasonic sensor subsequently confirms that the detected object is within this intrusion zone, the system immediately activates an audible alarm and instructs the ESP32-CAM module to capture an image of the event.
- Safe Zone (>110 cm): This zone is located outside the predefined protection boundary. Visitor activities occurring beyond this distance are considered safe and pose no immediate risk to the collection. Therefore, the system disregards detections outside the intrusion zone to minimize false alarms, while the device remains in standby mode until a valid intrusion event is confirmed.

III. Results and Discussion

A. System Implementation

At this stage, all hardware components were assembled into a fully integrated prototype, and the software was uploaded to the microcontroller to verify the functionality of the system.

- Hardware design.

  The hardware assembly process was divided into three main stages: the assembly of the control and power unit, the assembly of the sensor unit on the scanning mechanism, and the final integration of all components into the enclosure.

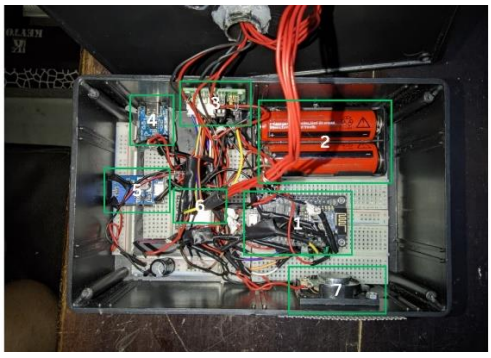


Fig. 3. Circuit of the control and power supply unit.

Fig 3 illustrates the main control and power management circuit of the system. The hardware components are described as follows: (1) NodeMCU ESP8266: The main microcontroller that serves as the central processing unit, responsible for system control, intrusion detection logic, and data communication. (2) 18650 Batteries: Rechargeable Li-ion batteries configured in parallel to provide a standalone power source with increased current capacity (mAh). (3) ULN2003 Motor Driver: A power interface module used to control the rotation direction and stepping sequence of the 28BYJ-48 stepper motor. (4) TP4056 Charging Module: A Li-ion battery charging and power management module equipped with overcharge protection to ensure safe battery operation. (5) MT3608 Step-Up Converter: A DC-DC boost converter that increases the battery output voltage from 3.7 V to a stable 5 V supply for powering the electronic components. (6) DFPlayer Mini: An MP3 audio playback module that stores and plays pre-recorded warning messages and alarm sounds. (7) Speaker: An audio output device that converts the electrical signals generated by the DFPlayer Mini into audible warning sounds.

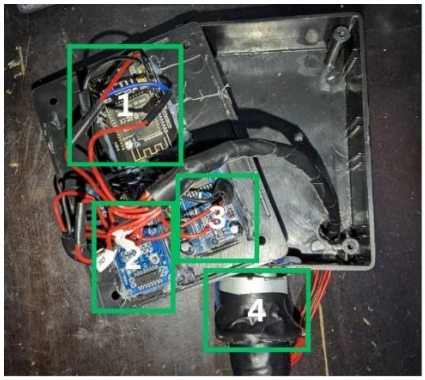


Fig. 4. Circuit of the sensors and camera.

Fig 4 illustrates the sensor and camera assembly of the system. The functions of each component are described as follows: (1) ESP32-CAM: A camera module that captures and transmits visual evidence whenever an intrusion is detected. (2) HC-SR04 Ultrasonic Sensor: A distance measurement sensor used to detect objects that enter or cross the predefined safety boundary. (3) Passive Infrared (PIR) Sensor: A passive infrared sensor that detects human presence or motion by sensing changes in the infrared radiation naturally emitted by the human body, thereby serving as the primary trigger for intrusion validation. (4) 28BYJ-48 Stepper Motor: An actuator that rotates the sensor platform in left and right directions, enabling continuous dynamic scanning of the protected area.

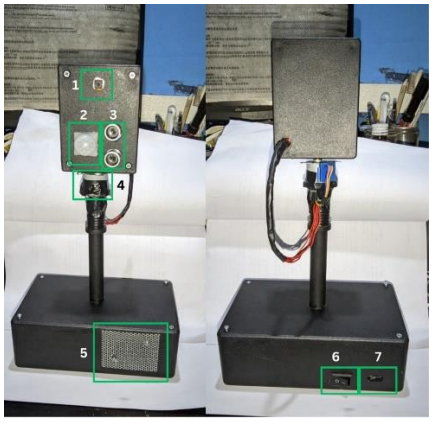


Fig. 5. Prototype of the virtual barrier system

Fig 5 presents the prototype of the virtual barrier system. The enclosure was designed with a matte black finish to achieve a minimalist appearance while minimizing visual distraction within the museum exhibition environment. The external components of the prototype are described as follows: (1) Camera Lens (ESP32-CAM): The camera lens is positioned at the top of the enclosure to provide a wide field of view for capturing visual evidence during intrusion events. (2) Passive Infrared (PIR) Sensor: A motion sensor that detects changes in the infrared radiation emitted by the human body, serving as the primary trigger for the

intrusion detection process. (3) Ultrasonic Sensor: A distance measurement sensor used to verify whether a visitor has entered or crossed the predefined safety boundary. (4) Stepper Motor: The actuator that rotates the sensor platform, enabling continuous multidirectional scanning of the protected area. (5) Speaker: The audio output unit that emits warning messages and alarm sounds through a protective metal grille. (6) Main Power Switch (On/Off): A physical switch used to manually turn the prototype on or off. (7) Charging Port: A USB Type-C charging port connected to the TP4056 charging module, allowing the 18650 rechargeable batteries to be recharged without disassembling the enclosure.

- User Interface (UI) design.

The monitoring application was developed for the Android platform using a direct-access approach, eliminating the need for a user login process to enable authorized museum personnel to monitor the virtual barrier system instantly. The following figures present the implemented user interface of the mobile application.

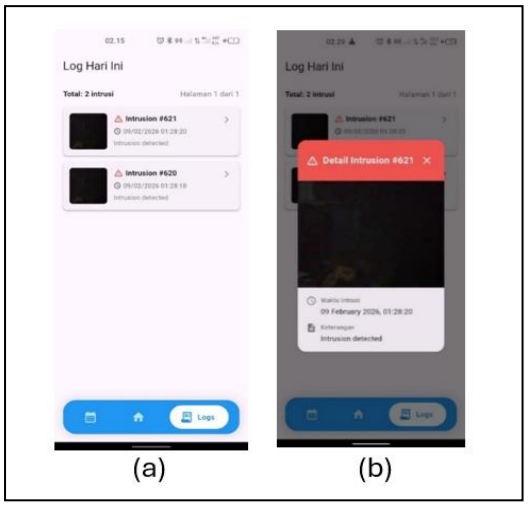


Fig. 6. UI of daily activity log

Fig 6(a) presents the daily activity log interface, which displays a real-time list of intrusion events recorded on the current day. The activity log is automatically reset at the beginning of each new day. Each entry includes a thumbnail image of the captured event along with the corresponding detection time. Fig 6(b) shows the intrusion detail interface, which is displayed when a user selects an entry from either the Daily Activity Log or the History interface. This interface presents the captured image in full resolution, allowing the detected individual or intrusion object to be clearly identified. In addition, the interface provides the precise date and timestamp of the incident to facilitate monitoring, verification, and post-event analysis.

Fig 7 illustrates the Intrusion History interface, which incorporates a calendar-based navigation mechanism for retrieving historical intrusion records. The interface allows users to view both a summary of the total number of intrusion events and the corresponding event list for a selected date.



Fig. 7. UI of the intrusion history

B. *Evaluation of IoT Data Transmission Latency*

Table 1 presents the results of the end-to-end transmission latency measurements, defined as the elapsed time between the detection of an intrusion event and the display of the corresponding event information and captured image in the Android monitoring application

TABLE I. IOT DATA TRANSMISSION LATENCY EVALUATION

No	Net. Type	Internet Speed (Mbps)		Detect. time	Display time	Latency	Status
		Down.	Upload				
1	*Hotspot* HP 4G	13.59	23.17	13:11:48	13:11:52	0:00:04	Success. Upload
2	*Hotspot* HP 4G	29.32	34.12	13:17:10	13:17:13	0:00:03	Success. Upload
3	*Hotspot* HP 4G	18.51	25.56	13:20:06	13:20:09	0:00:03	Success. Upload
4	Wi-Fi	20.87	24.87	13:26:22	13:26:23	0:00:01	Success. Upload
5	Wi-Fi	21.53	30.77	13:29:42	13:29:43	0:00:01	Success. Upload
6	Wi-Fi	25.38	35.68	13:33:00	13:33:02	0:00:02	Success. Upload
Rata-rata *Hotspot* HP		**20.47**	**27.62**			**0:00:03**	
Rata-rata Wi-Fi		**22.59**	**30.44**			**0:00:01**	
Rata-rata Keseluruhan		**21.53**	**29.03**			**0:00:02**	

Overall, the average system latency of only 2 seconds demonstrated that the ESP32-CAM module was capable of performing visual image acquisition and data transmission with a highly responsive, near real-time performance, provided that the network infrastructure offered a sufficient upload bandwidth (greater than 20 Mbps). Although the Android monitoring application experienced an average transmission delay of approximately 2 seconds, the local security function, namely the audible alarm, was activated immediately at the intrusion site and operated independently of network latency.

IV. CONCLUSION

This study successfully designed, implemented, and evaluated an intelligent IoT-based virtual barrier system to protect open-exhibition collections at the Maros-Pangkep PIG. By integrating a NodeMCU ESP8266, an ESP32-CAM module, PIR and ultrasonic sensors with AND-based sensor-fusion logic, a stepper motor for dynamic scanning, multilingual (in Indonesian, English and Makassar) voice

warnings, and an Android monitoring application, the proposed system provided automated intrusion detection, real-time local alerts, and visual evidence acquisition while preserving the aesthetic value of open museum exhibitions. Experimental results demonstrated that the PIR sensor effectively detected human motion within a range of 20-120 cm, the ultrasonic sensor achieved approximately 97% distance measurement accuracy with an error margin of 1-2 cm, and the average IoT data transmission delay was approximately 2 seconds under adequate network conditions. These findings indicate that the proposed system effectively enhanced museum collection protection by minimizing false alarms, improving intrusion detection accuracy, and enabling real-time monitoring and incident verification through a mobile application. Future research should focus on integrating artificial intelligence for object recognition, edge-based image processing, and cloud analytics to further improve the intelligence, scalability, and performance of smart museum security systems.

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