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Smart CCTV Face Detection System Based on the Internet of Things and Artificial Intelligence

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Abstract

The high rate of motor vehicle theft in Bandung City indicates that conventional security surveillance systems still have limitations in providing effective and responsive monitoring. Therefore, this study aims to design and implement a smart Closed Circuit Television (CCTV) face detection system based on the Internet of Things (IoT) and Artificial Intelligence (AI) capable of performing real-time monitoring and face detection. The research employed the User Centered Design (UCD) method, which consists of user needs identification, system design, implementation, and evaluation. The system was developed using a Raspberry Pi as the IoT edge device, a camera for image acquisition, the InsightFace algorithm for face recognition, and Firebase and the Telegram Bot API for data storage and notification delivery. The novelty of this study lies in the development of a smart CCTV system that integrates the User Centered Design (UCD) method, Internet of Things (IoT) technology, the InsightFace algorithm based on Artificial Intelligence (AI), an automatic pan-tilt module, and Telegram notifications into a single real-time security monitoring platform. The results show that the system achieved a face recognition accuracy of 92%, delivered Telegram notifications with an average response time of 2.8 seconds, and performed object tracking using the pan-tilt module with a response time of less than 0.5 seconds. In addition, the system successfully detected unknown faces, synchronized data to Firebase instantly, managed video storage automatically through a rolling buffer mechanism, and provided a responsive web-based dashboard. Based on the overall testing results, the developed system effectively improved security monitoring, facilitated remote surveillance, and met user requirements in accordance with the User Centered Design (UCD) approach.

Keywords: *Smart CCTV, Internet of Things (IoT), Artificial Intelligence (AI), Face Recognition, User-Centered Design (UCD)*

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1. INTRODUCTION

Increased crime rates, particularly motor vehicle theft, remain a serious issue that requires attention. Based on official data from the Bandung Metropolitan Police (Polrestabes Bandung), in 2024 there were 335 recorded cases of motorcycle theft, although this figure shows a 46% decrease compared to the previous year, which recorded 642 cases[1]. This data indicates that motor vehicle theft remains a real threat, thus requiring more effective monitoring and detection systems to support efforts in improving public safety.

One solution that can be implemented is the use of a smart Closed Circuit Television (CCTV) system that integrates Internet of Things (IoT) and Artificial Intelligence (AI) technologies. The integration of IoT in CCTV allows devices to be directly connected to the internet, enabling real-time monitoring and management through smartphones with faster response capabilities[2]. Through this technology, surveillance data can be accessed and managed remotely using mobile devices, thereby improving the flexibility and effectiveness of the monitoring process.

In addition, the application of AI, particularly through deep learning and digital image processing technologies, enables the system to automatically recognize faces, objects, and behavioral patterns without direct human intervention. Deep learning methods also provide high accuracy while maintaining a lightweight model, making them easier to implement across various platforms and strongly supporting real-time surveillance systems that require computational efficiency[3]. The combination of IoT and AI technologies results in a more innovative security solution as it improves monitoring effectiveness while reducing reliance on manual

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supervision, which is prone to errors due to fatigue and human limitations[4].

Several previous studies have explored the implementation of smart CCTV based on IoT and AI. Samsinar et al. developed a courier detection system using Smart CCTV based on the Internet of Things (IoT) with Telegram Bot communication. In this study, Raspberry Pi was used as the main controller to process and recognize commands sent to the system[5]. Furthermore, Pamungkas developed a User Interface for Smart CCTV monitoring systems using the Convolutional Neural Network (CNN) method based on IoT. This study utilized CNN as a deep learning technique for face detection, along with IoT technology to support real-time streaming and Telegram notifications when an unknown person is detected[6]. In addition, Mahbub and Warta developed a smart power monitoring system for CCTV based on IoT using the Scrum model, which enables real-time CCTV monitoring through a three-tier architecture consisting of user interface, business logic, and data management[7].

Based on these studies, it can be concluded that the use of IoT and AI in CCTV systems has contributed significantly to improving surveillance effectiveness. However, previous research has mainly focused on monitoring aspects, notification systems, and interface design. Moreover, there are still limited studies that integrate IoT and AI for face detection while considering user needs as the main focus of system development, including the lack of systematic analysis on the impact of optimizers and learning rates on detection performance[8].

This study develops a smart face recognition CCTV system based on IoT and AI using the User Centered Design (UCD) approach. This approach is used to ensure that the developed system is not only technically advanced but also adaptive to user needs. This research is expected to provide practical recommendations for the implementation of IoT- and AI-based smart CCTV systems in Indonesia, particularly in Bandung, to strengthen sustainable security systems. Furthermore, this study is expected to contribute academically to the field of information technology and security, as well as encourage further research development in the same area[9].

Considering the advancements in IoT and Artificial Intelligence technologies and the increasing need for more effective security systems, there is a demand for intelligent surveillance systems that are not only accurate but also responsive and user-oriented. This study addresses these needs by developing an IoT- and AI-based smart face recognition CCTV system using the User Centered Design (UCD) approach. The system integrates real-time face recognition, automatic camera tracking, and instant notification features to improve monitoring effectiveness. The results of this study are expected to provide both practical and strategic contributions in the implementation of intelligent surveillance systems to enhance public safety and comfort.

2. THEORETICAL FRAMEWORK

2.1 Closed Circuit Television (CCTV)

CCTV is a digital video system that transmits signals to a dedicated monitor for surveillance purposes. Modern CCTV systems have evolved into interconnected networks-supporting LAN, Wireless-LAN, or internet connectivity-and feature remotely operated cameras with pan, tilt, and zoom (PTZ) capabilities[10].

2.2 Internet Of Things (IoT)

The Internet of Things (IoT) is a concept aimed at extending the benefits of continuous internet connectivity to objects and living beings. Through embedded sensors, these entities are interconnected via local and global networks, enabling remote control and seamless data exchange. Fundamentally, IoT represents physical objects as unique virtual entities within an internet-based infrastructure[11].

2.3 Artificial Intelligence (AI)

Artificial Intelligence (AI) is a field of computer science that aims to develop systems capable of performing tasks that normally require human intelligence. AI uses mathematical models and algorithms to learn from data, recognize patterns, and make intelligent decisions. Key AI techniques include machine learning, neural networks, and natural language processing (NLP). AI has been widely applied in various fields, including speech recognition, facial recognition, autonomous vehicles, and healthcare[12]. Furthermore, Artificial Intelligence (AI) is a technology developed to drive innovation across various fields, including education. One of its core branches is Machine Learning, which enables systems to analyze data and contribute to solving complex challenges, such as cancer detection, climate change mitigation, and terrorism prevention*[13].*

2.4 Raspberry Pi Zero W

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Raspberry Pi is a compact single-board computer (SBC) widely used in embedded systems and Internet of Things (IoT) applications. It supports Python as its primary programming language and features essential hardware components, including a CPU, GPU, RAM, USB ports, HDMI, Ethernet, GPIO pins, and MicroSD storage. Due to its low cost, small size, and flexibility, Raspberry Pi is widely adopted for real-time monitoring, automation, and intelligent edge computing applications[14].

2.5 Firebase

Firebase is a cloud-based Backend-as-a-Service (BaaS) platform developed by Google that provides real-time data synchronization and cloud storage for mobile, web, and Internet of Things (IoT) applications. In this study, Firebase is used to store and synchronize face detection logs from the Raspberry Pi to the cloud in real time, enabling efficient data management and remote monitoring. Its real-time database and REST API support seamless communication between IoT devices and cloud services, making it suitable for smart CCTV applications[15].

2.6 Telegram

Telegram Bot is an automated application that can respond to messages, commands, and events through the Telegram Bot API. Each bot is configured using a unique API token generated by @BotFather, enabling integration with external systems. In this study, the Telegram Bot is used to send real-time alert notifications containing warning messages and images of detected unknown individuals, allowing users to monitor security events remotely and efficiently[16].

3. RESEARCH METHODOLOGY

This study uses the User Centered Design (UCD) method, which is a system development approach that focuses on user needs and usability. In the development of the smart face recognition CCTV system based on IoT and AI, the UCD method is applied as a structured framework to ensure that system design and implementation are aligned with user requirements throughout the development process. The UCD method consists of four main stages:

1. Plan the Human-Centered Process
This stage involves identifying the context of system usage, including surveillance environment, hardware components (Raspberry Pi, camera, and IoT network), and security problems that require real-time monitoring. Stakeholders and user roles are also identified to define system objectives.

2. Specify User and Organizational Requirements
This stage focuses on gathering functional and non-functional requirements, such as real-time face detection, face recognition, instant notification via Telegram, remote access via mobile devices, and data storage using Firebase.

3. Produce Design Solutions
In this stage, the system is designed and implemented using Raspberry Pi as an edge device, camera for image acquisition, and InsightFace for face recognition. IoT integration is used to enable real-time data transmission, while a pan-tilt mechanism is implemented for automatic camera tracking.

4. Evaluate Design
The system is evaluated through functional testing and performance analysis. Testing includes face recognition accuracy, response time of notifications, and system reliability. User satisfaction is measured using the System Usability Scale (SUS).

In addition, the system uses a face image dataset consisting of registered users and unknown (stranger) faces captured under different lighting and distance conditions. System testing is conducted using several scenarios, including normal lighting, low lighting, varying distances (1–2 meters), and real-time object movement. Evaluation is performed based on accuracy, response time, and usability results.

No	***Hardware Name***	***Function***	***Quantity***
1.	*Raspberry Pi Zero W*	*Serves as the main controller of the system*	*1*
2.	*Motor Control Module (PCA9685)*	*Controls servo motors via I2C..*	*1*
3.	*Camera Module V2*	*Functions as the image input device.*	*1*

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4.	*Servo Motor*	*Used to adjust the camera position.*	*1*
5	*Camera Cable*	*Cable used to connect raspberry pi*	*1*

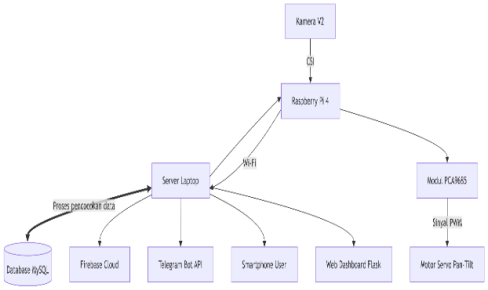
Tabel I : Hardware Used

No	Software Name	Version	Function
1.	*Firebase*	-	*Firebase functions as the database system.*
2.	*Telegram*	*13.15*	*Telegram is used as a notification platform for delivering detection results..*
3.	*Opencv*	*4.5.3.56*	*OpenCV is used to detect and process images captured by the camera.*
4.	*Draw.io*	*13.9.9*	*Draw.io is used to create system block diagrams, flowmaps, and flowcharts.*
5	*XAMPP*	*13.0*	*XAMPP functions as a localhost server and data storage medium.*

Table II : Software Used

The design process begins with the development of the hardware and software system architecture, followed by testing and analysis phases, ensuring that the developed system operates properly and in accordance with the established design objectives[17].

Figure 1. Block Diagram



Based on the system flow diagram, each component has a specific function that is integrated to form an intelligent surveillance ecosystem. The following describes the function of each component:

1. ***Raspberry Pi Zero W:*** *Functions as an IoT edge device responsible for acquiring visual data through the camera and executing mechanical control commands based on instructions received from the server.*
2. ***Camera Module V2:*** *Functions as the primary sensor for capturing visual data (real-time video streams), which are then transmitted to the server for processing.*
3. ***Laptop (AI Server):*** *Acts as the main computing center. OpenCV and InsightFace perform image processing, feature extraction, and face detection to authenticate subjects.*
4. ***PCA9685:*** *Functions as a PWM driver that receives instructions from the Raspberry Pi to precisely control servo motor movements.*
5. ***Servo Motors (Pan & Tilt):*** *Consist of two servo motors that mechanically move the camera, allowing it to continuously track the position of faces detected by the AI system.*
6. ***Firebase Realtime Database:*** *Used as a cloud-based database to store event logs, system status, and movement coordinates, while also serving as a synchronization medium between the server and the monitoring interface.*
7. ***Telegram Bot API:*** *Functions as a real-time notification channel that sends alerts and visual evidence (screenshots/videos) to users.*
8. ***Smartphone (User):*** *Serves as the end-user device for receiving instant notifications and remotely monitoring the system through the Telegram application and web dashboard.*
9. *Smartphone (Mobile Phone): Serves as the end-user device for receiving instant*

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notifications and remotely monitoring the system through the Telegram application and web dashboard. The system flowchart is presented in Figure 2.

The following flowchart illustrates the operation of the IoT- and AI-based smart face detection CCTV system. The flowchart describes the overall workflow of the system.

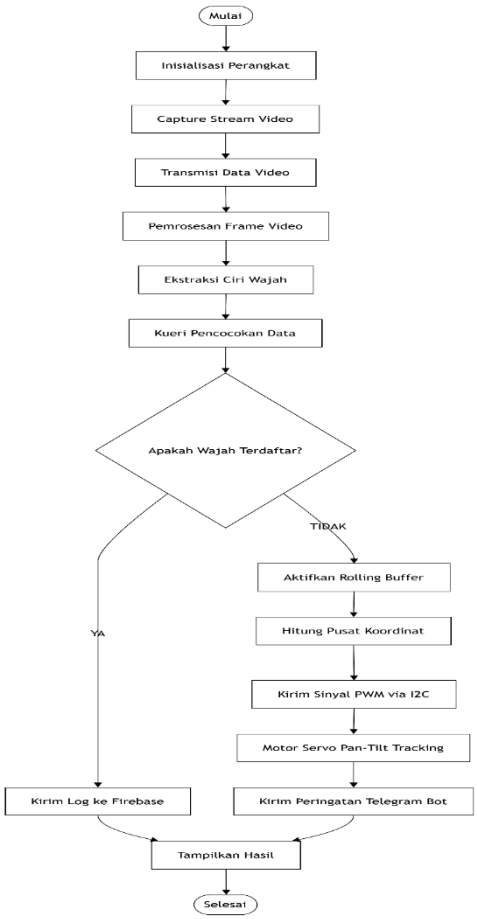


Figure 2. Flowchart

The hardware design stage includes the process of determining system requirements, creating the circuit design, and assembling the components to ensure that the device functions according to the intended objectives. This stage is carried out to ensure that all system components are properly integrated. The overall circuit schematic of the developed system is shown in the following figure. Figure 3 illustrates the schematic design of the "Internet of Things (IoT) and Artificial Intelligence (AI)-Based Smart Closed Circuit Television (CCTV) Face Detection System.

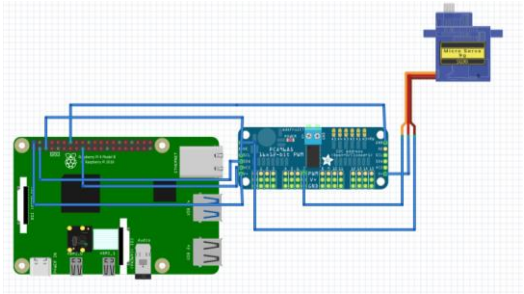


Figure 3. Schematic Diagram of the Proposed System

4. RESULTS AND DISCUSSION

A. Telegram Notification Implementation Result



Figure 4. Telegram Notification Implementation Results

Based on the testing results, the system successfully sent real-time Telegram notifications containing warning messages and

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photos of unknown individuals, as shown in Figure 4. These results indicate that the communication between the Raspberry Pi, AI server, and the Telegram Bot functioned properly through the internet connection, enabling reliable and instantaneous notification delivery to the user.

B. Hardware Implementation Results

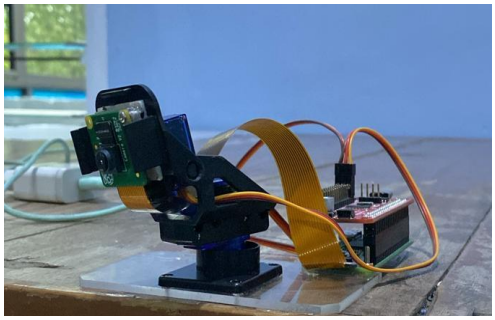


Figure 5. Hardware Implementation Results

The system, consisting of a Raspberry Pi, camera, and sensors, was successfully implemented as shown in Figure 5. Unlike previous studies that generally utilized separate modules, this system offers a more cohesive integration of AI detection and cloud logging. Its primary advantage is high responsiveness, enabling automated, real-time notifications and data synchronization. However, the system is limited by its dependency on stable internet connectivity and the impact of ambient lighting on detection accuracy, both of which serve as key considerations for future development.

C. Testing of Telegram Bot & Firebase Integration

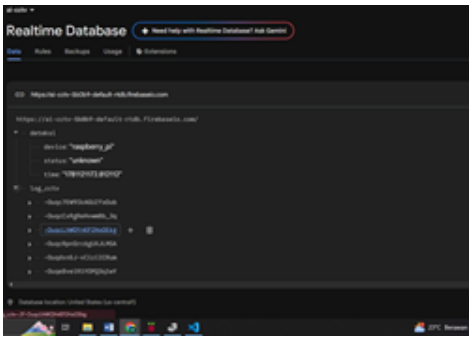


Figure 6. Testing of Telegram Bot & Firebase Integration

Testing of Telegram notifications and database synchronization was conducted to measure the latency of alert messages containing stranger photos and to ensure accurate real-time data logging in Firebase, as illustrated in Figure 6. The results demonstrated an average latency of 2.8 seconds, achieved through an event-driven architecture that triggers API calls immediately upon detection, thereby minimizing the delays typical of conventional polling methods. The observed fluctuations in response time were primarily attributed to variations in network bandwidth, indicating that while the system logic is optimized, its real-time performance remains inherently dependent on the stability of the internet infrastructure.

D. System Operation

The operation of the proposed system is divided into three main stages that work in a closed-loop cycle:

1. Acquisition and Transmission Stage (IoT Edge Side) At this stage, the Raspberry Pi equipped with the Camera Module V2 continuously captures video streams and transmits the captured frames to the laptop server through a local network (Wi-Fi) protocol. The use of a local network ensures very low latency, which is crucial for real-time security applications.
2. Intelligent Processing Stage (AI Server Side): At this stage, the laptop server receives the video stream from the Raspberry Pi. The OpenCV library processes the video into frames per second (FPS), while the InsightFace model performs facial feature extraction (embedding). The extracted facial feature vectors are then compared with the facial data stored in the MySQL database (XAMPP) to identify and recognize detected individuals.
Decision Logic:
Whitelist (Penghuni): If the detected face matches a record in the database, the system only records the attendance timestamp in the Firebase Realtime Database for logging purposes. Stranger (Unknown Person): If no match is found, the system activates the rolling buffer for automatic video recording to the hard drive, commands the camera to track the detected face, and sends an alert notification via Telegram.
3. Mechanical Response and Notification Stage (Output Side): At this stage, the server calculates the coordinates of the detected face within the video frame and sends the coordinate data back to the Raspberry Pi to control the servo motors through the PCA9685 module, ensuring that the camera continuously tracks and remains focused on the target. In addition, the system sends real-

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time alert notifications to the user's smartphone via the Telegram Bot API, including warning messages and captured images of the detected individual.

Web Dashboard: Users can remotely access the Flask-based web dashboard through a web browser to view live video streams and monitor system activity logs in real time.

The Camera acts as the system's eyes by capturing real-world visual information. The Laptop Server and AI function as the brain, analyzing and identifying detected individuals using artificial intelligence techniques. The Servo Motors serve as the hands, responding to object movements and ensuring continuous tracking of detected faces. Meanwhile, Telegram acts as the communication medium by providing instant notifications to the homeowner whenever a potential threat is detected. Unlike conventional CCTV systems that passively record events, the proposed system operates autonomously and proactively by making decisions to track detected subjects and generate real-time alerts.

E. System Testing

System testing was conducted to ensure that the developed system operates properly according to the proposed design. The testing process was performed on each component individually, followed by integrated system testing to verify that all components function correctly as a unified system.

1. Hardware Testing

Hardware testing was carried out to ensure that all devices used in the system function properly according to the design specifications. The results of the hardware testing are presented below.

2. Software Testing

Software testing was conducted to ensure that the system operates reliably without experiencing crashes or running out of storage space during extended periods of operation.

Based on the tests that have been conducted, the combined hardware and software testing results are presented in Table III.

No	*Component/ Scenario*	*Test Parameter*	*Condition*	*Result*	*Description*
1	*Face Detection*	*Recognition accuracy*	*Distance 1–2 m, normal lighting*	*92 %*	*Successful*
2	*Face Detection*	*Stranger face detection*	*Real-time condition*	*Successful*	*Detected as Stranger*
3	*Servo Tracking*	*Movement response (pan & tilt)*	*Horizontal/ vertical object movement*	*< 0.5s*	*Smooth and stable movement*
4	*Telegram Bot*	*Notification delivery speed*	*Stable Wi-Fi connection*	*2.8s*	*Notification and photo successfully delivered*
5	*Firebase*	*Log data synchronization*	*Cloud upload*	*Instan*	*Logs recorded on time*
6	*Rolling Buffer*	*Memory management (1 hour)*	*Continuous recording*	*Stable*	*Old files automatically deleted*
7	*Web System*	*Dashboard accessibility*	*Local network connection*	*Responsive*	*No lag during access*

Table III : Results Of Hardware And Software Testing

5. CONCLUSION

Based on the design, implementation, and testing of the IoT- and AI-based smart CCTV system, the following conclusions can be drawn:

1. *The proposed system successfully implements a client-server architecture, where the Raspberry Pi functions as an IoT edge device and a laptop is used as the AI processing server, enabling an efficient*

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division of tasks between hardware and software components.

2. *The integration of the InsightFace-based facial recognition model enables real-time user authentication by distinguishing between registered users (whitelist) and unknown individuals with satisfactory performance.*
3. *The servo-based camera tracking system supported by the PCA9685 module provides stable and responsive movement, improving the surveillance coverage area based on detected facial positions.*
4. *Integration with IoT services such as Telegram Bot API and Firebase allows real-time monitoring and notification delivery with efficient response time.*
5. *The implemented data management strategy, including rolling buffer and automatic file deletion, contributes to maintaining storage efficiency and ensuring continuous system operation.*
6. *Overall, the system demonstrates effective implementation of IoT- and AI-based surveillance. However, its performance is still limited by environmental lighting conditions and reliance on stable internet connectivity.*

6. SUGGESTIONS

Based on the results of the study, several suggestions for future system development are as follows:

Based on the results of this study, several suggestions for future system development are as follows:

1. *The facial recognition system can be further improved to increase detection accuracy under various environmental conditions, particularly in low or unstable lighting conditions.*
2. *Future research can focus on optimizing AI computation processes to improve data processing efficiency, ensuring the system performs well even as the amount of stored facial data increases.*
3. *The system can be further developed by implementing AI processing directly on edge devices such as Raspberry Pi, in order to reduce dependency on servers and internet connectivity.*
4. *The monitoring and notification features can be enhanced through the development of a mobile application, enabling users to access security information more easily and flexibly.*

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