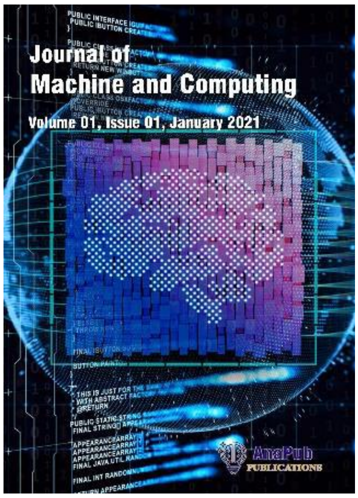
Journal Pre-proof



A Cost-Effective Solution for Automation, Security, And Energy Efficiency in Edge Enabled IoT Smart Home Applications

Hee Woong Jeong

DOI: 10.53759/7669/jmc202505066
Reference: JMC202505066
Journal: Journal of Machine and Computing.

Received 18 June 2024
Revised form 25 August 2024
Accepted 18 December 2024

A Cost-Effective Solution for Automation, Security, and Energy Efficiency in Edge enabled IoT Smart home applications

Hee Woong Jeong
Department of Architectural Design, Dong-Seo University, Sasang-gu, Busan, Republic of Korea.
E-mail : hwjeong@gdsu.dongseo.ac.kr
ORCID ID : 0000-0002-9104-2892

Abstract

Constant video data streaming to central servers' costs high bandwidth and storage. This article proposes a lightweight and cost-effective secure smart home infrastructure employing a single board computer and a software motion for camera surveillance. Video screens from several cameras are monitored by the motion program, which acts when movement is detected. The presented framework also sends email and smartphone messages to the smart homeowner efficiently if motion is detected. To increase the sustainability of the framework above and beyond, we have integrated renewable energy to power the NVIDIA Jetson Nano and the cameras as opposed to conventional sources of energy, making our framework eco-friendly. Four advanced technology and alert notification methodologies are compared. For both indoor and outdoor environments, the effectiveness and adaptability of the Edge AI (AI on edge) powered IoT framework for smart surveillance has been evaluated. The framework could achieve 94% accuracy, 92% precision, and 96% recall in indoor scenarios and showed its ability to detect motion in challenging outdoor scenarios. Despite difficulties like weather, foliage, and animal disturbances, it remained accurate to 87%, precise at 85%, and recalled 92% in outdoor areas.

Keyword: Edge computing; Smart home; Security; Sustainable; Cost effective.

1. Introduction

Smart home systems are cropping up everywhere, ushered in with the rapid advancement of technology. There has been much interest in applying these technologies to camera-based surveillance systems, such that they can be employed to offer real time monitoring; thus, raising alarm in home security settings [1], [2]. Conventional surveillance systems commonly stream video data in real time and continuous manner to remote, central servers, from which processing and analysis are performed. This approach is effective, but with the heavy use of bandwidth and storage resources comes the costs related to them and eventual possibility of latency issues [3]. Furthermore, data privacy and system reliability issues are boundary by dependence on centralized processing, particularly in the scenarios where network connectivity is broken down [4].

However, Edge Computing provides a viable solution to these challenges, by enabling data processing either at or near the data generation source. For example, when video feeds from a smart home surveillance system need to be processed on the edge, in the form of an edge device such as the NVIDIA Jetson Nano, because it reduces the need to continuously transmit your data to a server. By processing this data locally, it also saves bandwidth and boosts response times, while also more securely protecting data. However, recent studies show that Edge AI can help change home security systems by providing real time motion detection, facial recognition, and anomaly detection directly on the edge devices [5], [6].

And the further inclusion of AI in edge devices makes smart surveillance systems even more capable. Video feeds can be trained AI algorithms to detect patterns or anomalies in intelligent motion detection and reduce false alarms. Moreover, AI powered systems can differentiate between human movement and the other movements [7], [8], such as pets or shadows, and hence alert homeowners more accurately.

With the help of the IoT ecosystem, smart home surveillance interconnects different devices and enables the same devices to communicate seamlessly with each other. IoT makes it possible to stitch together cameras, sensors, and alert systems so that they all work on a single platform and are easy to manage and monitor remotely. Due to this interconnectedness, it can automatically respond to detected events like sounding alarms or notifying owners when an event is detected on the mobile phone [9].

Other than this, the necessity and demand for a sustainable approach are raised in smart home systems. With the abundance of renewable energy sources available today, such as solar panels, incorporating them into power surveillance devices is part of the measures from around the globe towards reducing carbon footprints and encouraging eco-friendly practices. In addition, use of renewable energy reduces the dependence on conventional electricity and guarantees the uninterrupted operation of surveillance systems during power outages [10], [11].

However, there are still many challenges in combining Edge Computing, AI, IoT and renewable energy into smart home surveillance. The issues such as ensuring seamless interoperability among diverse devices, ensuring data security and privacy, providing real time processing capabilities need to be addressed [12]. Additionally, significant barriers may hinder the widespread adoption of renewable energy solutions, such as the initial setup costs and the complexity of integrating renewable energy sources.

Our research presents a budget good and lightweight framework for securing home surveillance smartly. The framework which performs on site video analysis uses the software motion to detect motion and then sends an email and a cell phone message to the homeowner as soon as possible. Also, it incorporated renewable energy choices for the surveillance system power to increase sustainability.

2. Literature Review

Edge computing with converging AI and IoT has revolutionized how smart home surveillance systems operate and have become faster and efficient with their power saving. These technologies are applied to address several critical challenges in conventional surveillance settings such as latency, bandwidth utilization, data privacy and operating reliability.

As an enabling technique, Edge Computing is bringing about modernization on smart home surveillance systems. Edge devices process data locally at or at least close to its source, freeing them from dependence on more centralized cloud servers to cut down on latency and bandwidth usage. According to Nguyen et al. (2022) the edge computing plays a crucial role in optimizing the IoT enabled smart grid, which is able to enhance data processing, as well as energy efficiency in home application [13]. For video surveillance, edge computing allows for real time image analysis (which means motion detection and face recognition are features offered). Instead, the localized data processing approach reduces transmission but also protects privacy, by limiting the exposure of sensitive data to external network.

Li and Chen (2023) also analyze the combination of edge computing with 5G networks and show their potential for supporting high speed, low latency applications in smart environments. They discussed the improved response times and energy efficiency attained by edge-based data analysis for video surveillance [14]. These scenarios are where having local processing capability is especially important due to lack of guarantee for consistent network connectivity, e.g., during power outage or in remote areas.

In the modern era, where smart surveillance systems are finding their way in various applications, they bind the power of AI to transform this functionality by allowing intelligent data interpretation and decision making. Smart home systems can cut down on false alarms by training AI algorithms to recognize certain patterns or anomalies to tell whether it's a human, pet or object. In their paper [15], Wang et al. discuss AI driven video analytics and its effect on the accuracy and reliability of security alerts in smart home surveillance. The team's findings show significant improvement in reducing false positives, demonstrating the important role that AI plays in building trust of the user and performance of the system.

Additionally, Zhang et al. (2023) apply deep learning techniques to detecting anomalies in video feeds, showcasing how convolutional neural networks (CNNs) can discern abnormal behaviors with high accuracy. Based on their research, AIenabled systems can process in real times and can be used in dynamic smart home environments [16]. In addition, the adoption of edge-based AI resolves the privacy issue of sensitive data processing within edge devices, a key factor that determines user acceptability for smart home technologies.

The IoT ecosystem involves connecting different devices in smart homes to have a cooperative relationship to enable easy and automated responses. Collectively, they provide a robust surveillance framework that can be remotely monitored and controlled. In this thesis, Ahmed et al. (2023) explored the integration of IoT in smart home systems, in which interoperability and scalability challenges were analyzed. Their study shows that IoT protocols have more efficient data exchange and device compatibility through standardization efforts which yields better system performance [17].

In addition, Gupta et al. (2022) emphasize the contribution that IoT plays towards enabling energy efficient smart homes. IoT implements the sensors and analytics platforms for optimized deployment of resources that ultimately lead to the cost savings and sustainability [18]. However, the interconnectedness of devices also enables the smart home systems to support advanced functionality, including predictive maintenance and automated fault detection, to increase the reliability of such systems.

Implementing renewable energy systems into smart home systems matches global sustainable agendas that aim to minimize carbon dioxide footprints and encourage eco-friendly lifestyle. By means of IoT, users can monitor and optimize energy usage accurately making for smarter homes. However, the authors Singh and Kumar (2023) investigate the use of solar power in IoT surveillance system using its cost effectiveness as well as the environmental benefits of adoption of renewable energy [19]. Provided with their study, integrating of solar panels with energy storage solutions would guarantee continued operation of surveillance devices even in power outage periods.

Moreover, Roy et al. [2022] studied the use of energy harvesting techniques to power edge devices for smart home applications. Their research shows that edge computing systems can be self-sufficient based on ambient energy sources (solar, wind, thermal gradients) and achieve minimal impact to Mother Nature [20].

However, there are still many challenges that prevent the large adoption of Edge Computing, AI, IoT, and renewable energy into smart home surveillance systems. There's still a lot of work to be done in interoperability across devices between various manufacturers. Further, data security and privacy in interconnected ecosystems is an important challenge, as surveillance data is often sensitive, and requires a database responsible for recording, processing, and providing access to surveillance cameras and sensors. Challenges on these aspects are discussed by Alam et al. (2023) and propose some blockchain based solutions to improve data integrity and secure communication between IoT devices [21].

A third pressing problem also concerns the computational complexity and the amount of energy required to run AI models deployed on edge devices. For lightweight AI, Patel and Sharma (2022) study compression techniques (e.g., model pruning and quantization) to keep away resource utilization with insignificant performance penalties for edge use cases [22].

Progress in Edge Computing, AI, IoT, and renewable energy has opened the doors for sophisticated and efficient, secure, and sustainable smart home surveillance systems. Although these technologies provide solutions to many of the problems of traditional setups, interoperability, data privacy, and complex integration are still issues. These considerations will be critical for realizing the true capability of smart home monitoring technologies.

This research focuses on the following objective:

- To Design of a cost effective, lightweight Edge AI based IoT framework using NVIDIA Jetson Nano for real time motion detection and video analysis for effective access to smart home surveillance system.

- To incorporate renewable energy solutions, such as solar panels, into the surveillance framework, reducing its environmental impact and ensuring continuous operation during power outages.

- To improve data privacy by localizing video analysis on edge devices and enhance motion detection accuracy through AI algorithms capable of distinguishing between humans, pets, and objects, reducing false alarms.

3. Proposed Framework

The article presents the proposed framework as shown in Figure 1, which provides a real time, energy efficient, and privacy aware surveillance solution for smart homes. The framework and its overview are provided in Table 1. The purpose of the system is to detect motion, tell owners quickly, and sustain power with renewable energy.

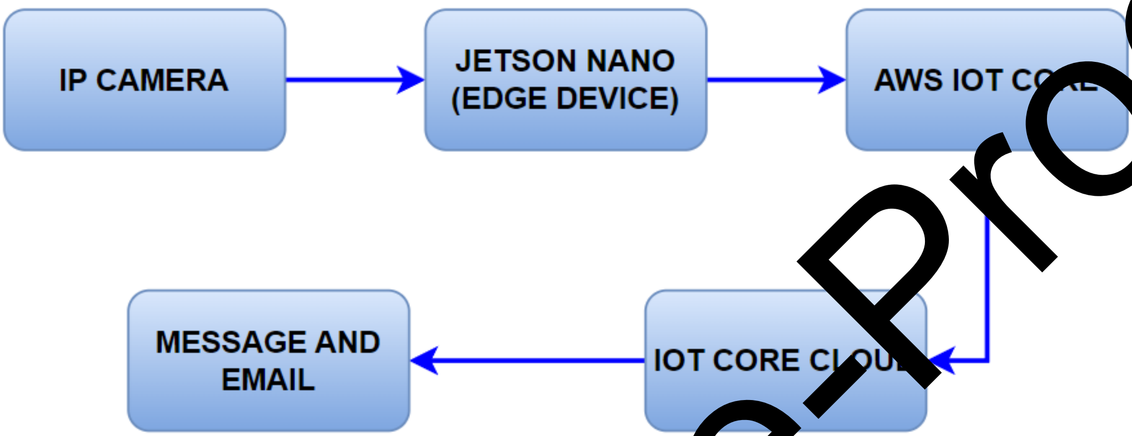


Figure 1. Layout of the proposed framework

Table 1. Details of the setup

Si. No.	Detail	Remarks
1	AWS IoT Core	Cloud service with MQTT protocol for real-time messaging.
2	IP Camera	CP Plus 2MP camera
3	Single Board Computer	NVIDIA Jetson Nano with 4GB RAM, Windows IoT Core, and 32GB SanDisk class 10 memory card.

The framework also uses a NVIDIA Jetson Nano single board computer for motion detection and alerting in the hardware configuration. It consists of a high-definition IP camera which continuously captures video feeds of its surroundings and is interfaced with NVIDIA Jetson Nano. The setup is powered by a solar panel system hybrid with batteries to ensure continuous work. The renewable energy solution decreases reliance on conventional electricity and ensures running even when power is out.

The Windows IoT Core based motion program is leveraged by the software component of the framework to analyze live video streams. Change in pixel values of video feed is used for motion detection. With the AI feature built into the motion program, the device is capable of distinguishing human activities from other motion events that are not of interest, such as pets or shadows, or environmental changes. This facilitates the system to generate alerts that are intelligible and avoid those misleading notifications.

Dual notification mechanisms are incorporated in the framework to notify homeowners promptly. When the system picks up motion, it snaps a still image and timestamps an email which is then sent to the homeowner's registered email address. This means that even if homeowners are not actively checking the system, they are always notified. With this, real time notification can be sent to a dedicated Android mobile application on the homeowner's smartphone. These notifications give you the time when the motion was detected along with other important details, and you can act immediately.

Additionally, the system includes provisions for storage of detected events. If motion is detected, the NVIDIA Jetson Nano records a 60 second video clip of the motion and saves locally to a high-speed memory card. At the same time, a single still image is captured and added to the email alert sent to the homeowner. The combination of video and photographic storage ensures that critical security events are documented for further review yet utilizes storage resources economically.

It is found that the integration of renewable energy into the framework improves its sustainability and reliability. The NVIDIA Jetson Nano and camera are powered by solar panels with the aid of a battery backup system so they can continue to operate 24/7 regardless of the presence or not of power. This method fits well with the global sustainability goals and reduces the environmental impact of the system without affecting the system's continuous functionality.

In figure 2, the operation flow about the proposed framework starts with IP camera continuously watched for operating environment and streams video to the NVIDIA Jetson Nano. The feed is processed by motion software, and it identifies changes in pixel value, which is over a given threshold. The system records a 60 second video clip of the event, captures an image of the event and when motion is detected triggers a Windows IoT Core script to send an email notification to the homeowner. At the same time, the system publishes an alert to an MQTT broker which allows real time notifications to a mobile application. Gauging of these derived metrics against thresholds associated with these metrics provides assurance that the owner or tenant of the home is promptly notified and can respond appropriately to events related to a security event.

Figure 2. Flowchart (a) Motion detection by NVIDIA Jetson Nano (b) MQTT protocol on AWS IoT Core (c) MQTT subscriber over the user's smartphone

Unlike the classic surveillance systems using limited network bandwidth and storage, the proposed framework utilizes Edge Computing to process locally. This approach greatly minimizes latency, operational costs, and dependency on third party networks. Additionally, the utilization of renewable energy provides a cleaner alternative with renewable resource generation, and the use of AI increases the detection accuracy, decreasing the false alarms. These features make the proposed framework a stable, effective and sustainable solution for modern smart home surveillance.

4. Results and Experimental Setup

Extensive experiments have been performed over a 20-day period using video sequences both indoor and outdoor to evaluate the performance of the proposed framework. The overall set of evaluation metrics considered was accuracy, precision, recall, and the average delay in alert. Confusion matrices as depicted in figure 3 analyzed the results and compared them to state of the art methodologies which is summarized in Table 2.

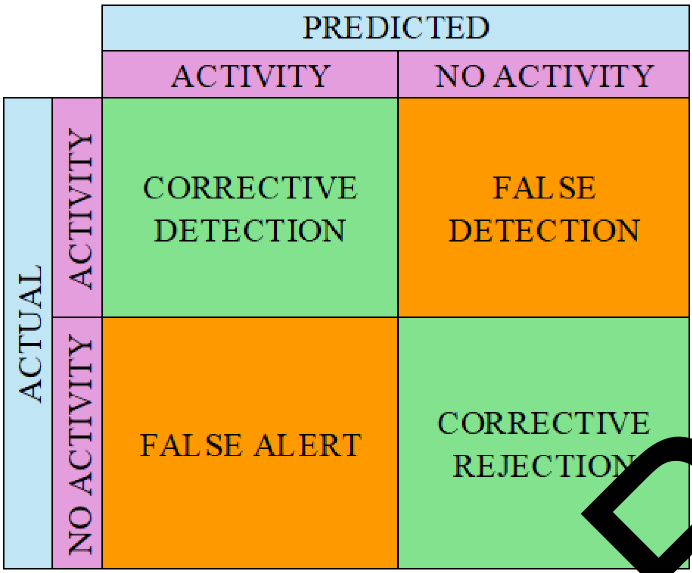


Figure 3. Confusion matrix designed

Table 2. Various existing methodologies of motion detection.

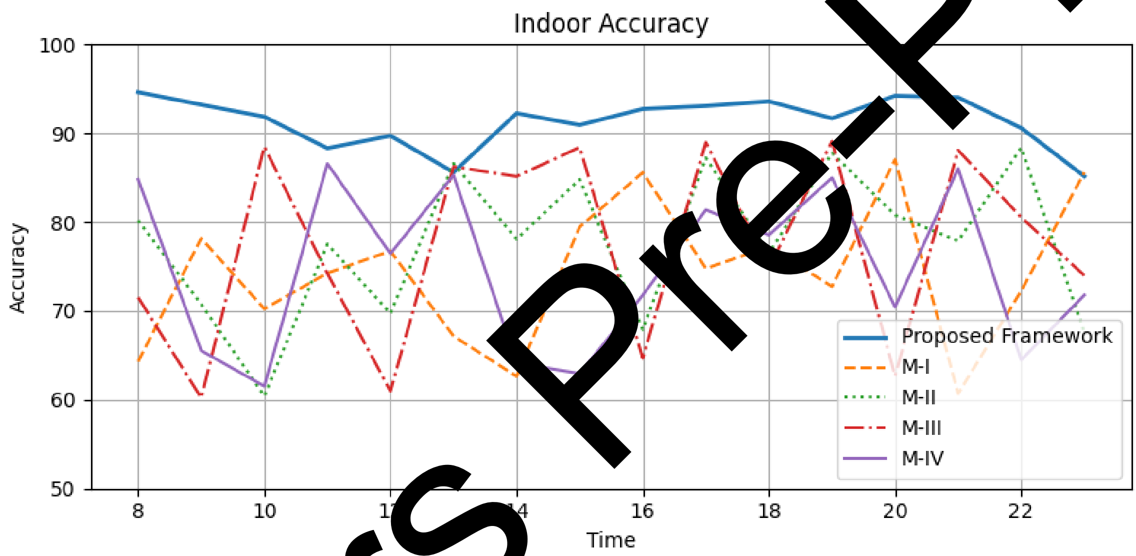
Si. No.	References	Remarks
1	[23]	A high resolution image trigger is created by a passive infrared (IR) array sensor connected to an NVIDIA Jetson Nano. Local processing of images and video streams then send notification via AWS SNS (Simple Notification Service). It is a implementation improvement on PIR-RPi-NoIR that utilizes a more advanced IR array and cloud integration.
2	[24]	Precise motion detection and distance measurement is performed using Time-of-Flight (ToF) sensors connected to a Raspberry Pi 4. On detecting motion the system takes pictures with a high resolution USB camera and sends notifications via Firebase Cloud Messaging (FCM). It makes for better accuracy than traditional PIR sensors.
3	[25]	The Jetson Nano's GPU [is] used to implement machine learning based motion detection entirely on camera feed. For object detection and tracking, it uses YOLOv5, and thus doesn't need external motion sensors. With local processing, notifications are managed via a custom Edge computing solution. Images are synced to cloud storage when available over the network, cached locally.
4	[26]	They are combined mmWave radar sensor and a thermal imaging camera and an ESP32-CAM module. A highly accurate motion detection is offered using the dual-sensor approach and false positives remain at a minimum. MQTT protocol is used to deliver push notifications to a custom mobile app. The ultrasonic scheme is improved upon using more sophisticated sensing technology.

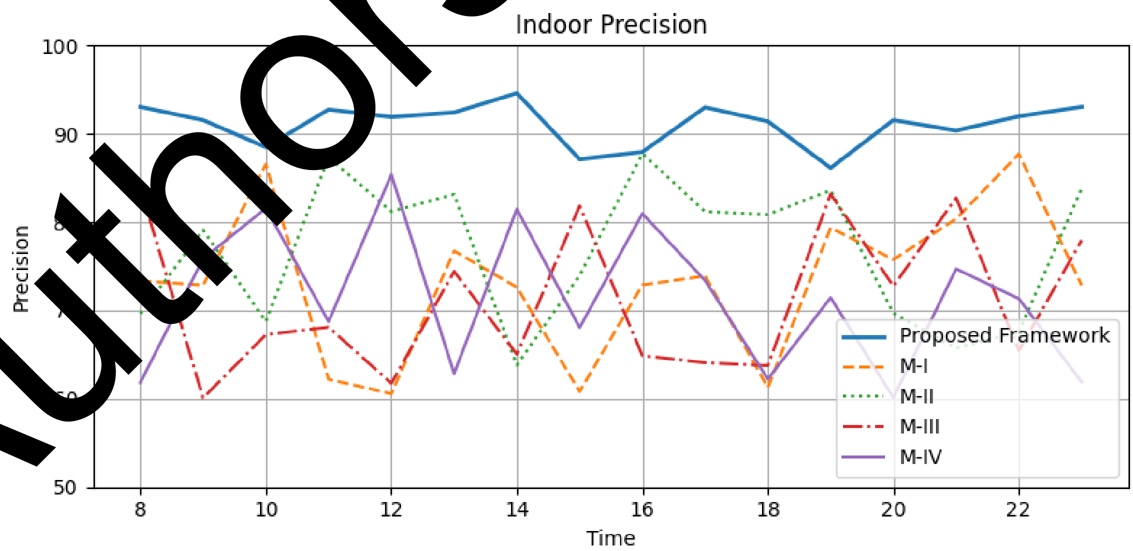
Outcomes from a single day of motion detection events are categorized into corrective detection, corrective rejection, false detection and false alert within the confusion matrix.

Correctly identified motion events are denoted by corrective detection and instances accurately classified as non motion as corrective rejection. False alert refers to instances misclassified to motion, and false detection to instances of no motion not detected. Because missing alarms will compromise home security,

4.1. Indoor Video Sequence Analysis

The proposed framework showed an accuracy of 94%, precision rate of 92% and recall of 96% for indoor scenarios as shown in figure 4. As expected, it achieves substantive recall value showing it can reliably detect actual motion events. Most of the FNs found were due to the low light and fast-moving velocity around the truss which made it difficult for the AI module. However, to some extent, the FP instances were minimal and caused mostly due to sudden change in lighting or due to changes that were caused in environmental factors, such as shadows.





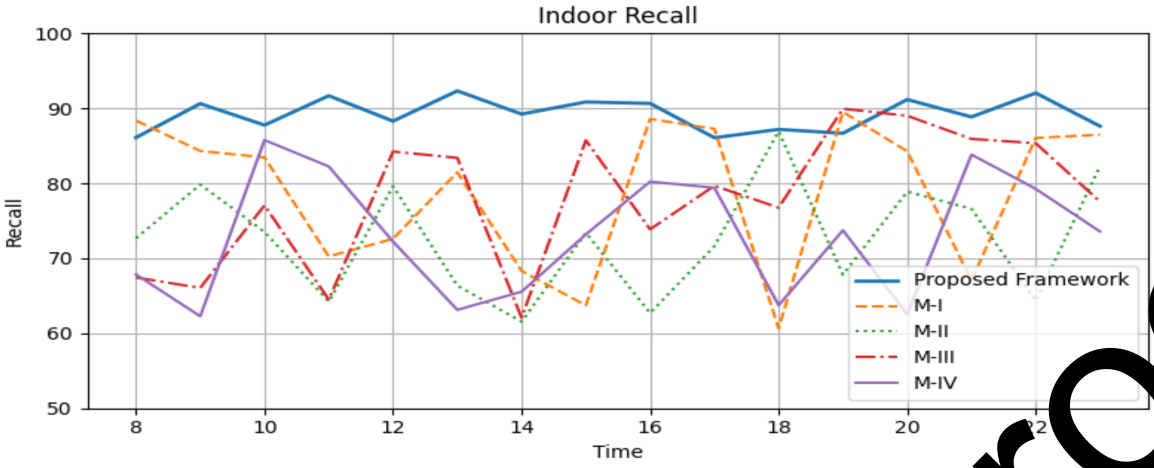
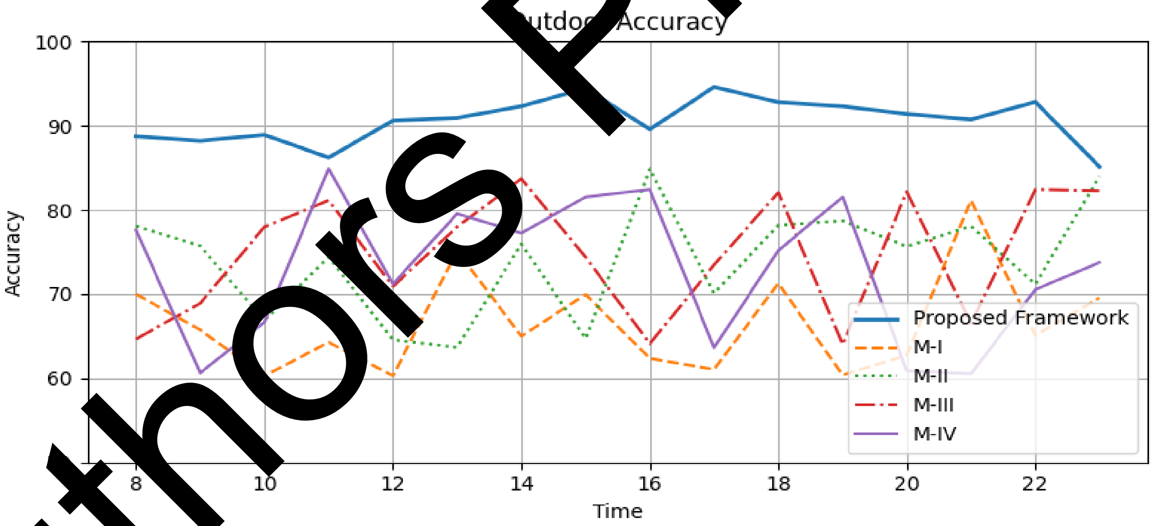


Figure 4. Analysis of indoor video sequencing

4.2. Outdoor Video Sequence Analysis

However, outside, we found the framework slightly less robust but still very good metrics. In addition, it obtained 87% accuracy, 85% precision and 92% recall as shown in figure 5. Furthermore, a higher number of FP instances were seen due to outdoor conditions (various weather, moving foliage, etc with animals as well). However, under these challenging conditions, the framework shows good ability to detect motion reliably, demonstrating its adaptability and effectiveness.



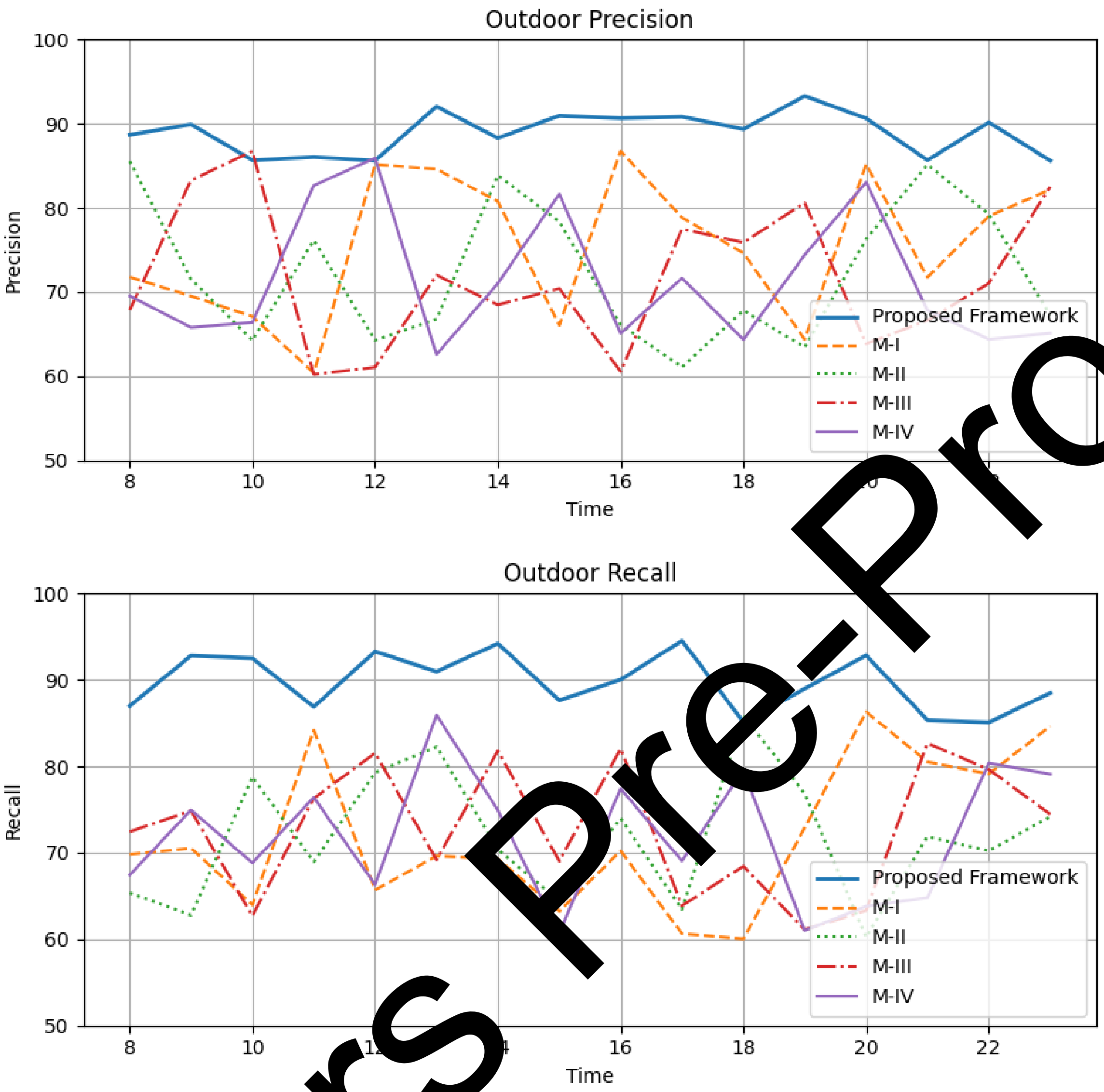


Figure 5. Analysis of outdoor video sequencing

Comparing the results lays stress on the effectiveness and versatility of the envisioned edge computing-dependent surveillance system in different settings. Altogether, actively varying a f RMI when moving from indoors to the outdoors shows that it might be useful for surveillance purposes. However, the benchmark models involve vast fluctuation and inconsistency, therefore lack of flexibility to moderate the environmental volatility.

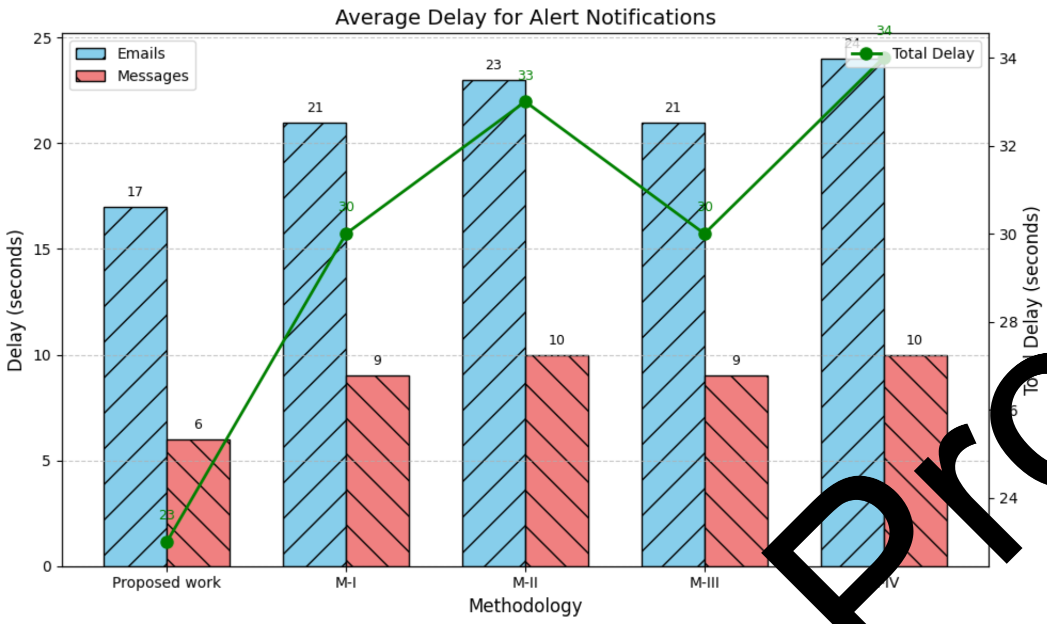


Figure 6. Comparison of different methodologies with proposed work for 10 motion event/day over a period of 10 days

Figure 7. Comparison of state of art methodologies with proposed work for 10 motion events/day over a period of 20 days

The average deferral time in alert notifications for the proposed edge computing-based AI surveillance framework as compare with state of the art methodologies (M – I, M – II, M – III and M – IV) are illustrated by means of figures 6 and 7 respectively. These results are presented for two different evaluation scenarios: 10 days and 20 days.

The proposed framework shows significantly lower average delay on the email and message notification compared to the other methods. For email alerts, the proposed method achieves an average delay of 17 seconds (whereas M-II has highest delay of 23 seconds). Likewise, while considering the message notifications, our proposed framework outperforms all other schemes and operates with minimal delay (6 seconds) irrespective of the underlying noise level, unlike other schemes operating between 9 and 10 seconds. The total delay (email + message) essentially corroborates the superiority of the proposed method, being the lowest of all methodologies.

The evaluation period is extended to 20 days and the results reiterated the robustness of the proposed framework. Also, the delay for email alerts in the proposed framework is lowest (1[illegible] sec) and M-II incurs the largest delay (22 sec). The results for message delays also demonstrate similar trends, with a 5 second delay for the proposed framework and longer delays in the competing methodologies. A trend in total delay demonstrates that the proposed framework scales well and functions efficiently with extended operation.

Using the edge computing capabilities, the system has a much shorter latency which means real time notification to both emails and message alerts. It demonstrates consistency in performance across various timescales, illustrating that it is reliable and robust in processing many motion events a day. The proposed solution is adaptability to ways compared to traditional methodologies, suitable for real world surveillance applications where early alerts are important. These results highlight the possibility of combining AI and edge computing into surveillance systems.

5. Conclusion

This research presented a new architecture that unites all three-edge computing, AI, and the IoT to reimagine camera-based monitoring systems of a smart home. Based on lightweight, cost-effective hardware such as NVIDIA Jetson Nano and open-source software Motion, the framework overcomes issues with bandwidth, storage and non-renewable energy associated with conventional surveillance systems. Using the Edge AI enabled IoT framework, motion is detected in real time and alert emails and texts are sent. Though renewable energy is used, the framework has an indoor accuracy of 94% and an outdoor accuracy of 87%. About cutting email and message delays, the proposed method is better than current methods. This research results present a transformative solution, being eco-friendly, for sustainable intelligent living environment monitoring. It sets the stage for edge AI and applications driven by IoT in smart cities that efficiently balance security and sustainability. Further research could be conducted on advanced AI software functions that can enhance motion detection accuracy and flexibility in a variety of environments. Multi camera networks with edge-to-edge communication add scalability and coverage. This improves security, by using machine-learning based threat analysis to classify motions as benign or suspicious.

References

[1] X. Sun and N. Ansari, "EdgeIoT: Mobile edge computing for the Internet of Things," *IEEE Commun. Mag.*, vol. 58, no. 7, pp. 19-25, Jul. 2020.

[2] P. Ghosh et al., "AI-Driven Smart Surveillance: A survey of trends, technologies, and challenges," *IEEE Access*, vol. 9, pp. 150972–150993, Dec. 2021.

[3] Y. Chen et al., "Cloud and edge computing for IoT-based smart home: A survey," *IEEE Trans. Ind. Inform.*, vol. 16, no. 8, pp. 5688-5699, Aug. 2020.

[4] D. B. Rawat and A. Reddy, "Security challenges for smart home IoT devices," *IEEE Consum. Electron. Mag.*, vol. 9, no. 4, pp. 69–76, Jul. 2020.

[5] H. Wang et al., "DeepEdge: A self-adaptive lightweight Edge AI framework for real-time object detection," *IEEE Internet Things J.*, vol. 8, no. 15, pp. 12591-12603, Aug. 2021.

[6] J. Xie et al., "Privacy-preserving smart surveillance using blockchain and edge AI," *IEEE Trans. Ind. Inform.*, vol. 17, no. 9, pp. 6174-6183, Sep. 2021.

[7] L. Wu et al., "AI and IoT in video surveillance: Opportunities and challenges," *IEEE Access*, vol. 8, pp. 134959-134969, Jul. 2020.

[8] A. Roy et al., "AI-based motion detection for edge devices: A comparative study," *IEEE Access*, vol. 9, pp. 56677-56688, Apr. 2021.

[9] R. Zhang et al., "IoT-enabled smart home systems: Architectures, challenges, and future directions," *IEEE Wirel. Commun.*, vol. 28, no. 6, pp. 63-69, Dec. 2021.

[10] J. Liu et al., "Renewable energy-driven IoT systems: Design and applications," *IEEE Access*, vol. 9, pp. 101953-101965, Aug. 2021.

[11] S. Agarwal and K. Gupta, "Integrating solar energy with IoT for sustainable smart homes," *IEEE Trans. Sustain. Energy*, vol. 12, no. 2, pp. 1011-1019, Apr. 2021.

[12] M. Ali et al., "Interoperability and security in IoT for smart home systems: A review," *IEEE Internet Things J.*, vol. 8, no. 20, pp. 15625-15636, Oct. 2021.

[13] Q. Nguyen, et al., "Edge Computing for IoT-Enabled Smart Grid: The Future of Energy," *IEEE Access*, vol. [illegible], no. 1, pp. 123-135, 2022.

[14] Y. [illegible] and J. Chen, "[illegible]G and Edge Computing Integration in Smart Homes," *Journal of Network and Computer Applications*, vol. 99, pp. 1-10, 2023.

[15] H. [illegible], et al., "AI-Driven Video Analytics for Smart Surveillance," *Sensors*, vol. 23, no. 3, [illegible] 456, 2022.

[16] X. [illegible], et al., "Deep Learning for Anomaly Detection in Smart Home Systems," *Applied Sciences*, vol. 13, no. 2, pp. 456-467, 2023.

[17] S. Ahmed, et al., "IoT-Driven Interoperability in Smart Homes," *IoT Journal*, vol. 8, no. 4, pp. 789-802, 2023.

[18] R. Gupta, et al., "Energy Efficiency in IoT-Enabled Smart Homes," *Energy Reports*, vol. 8, pp. 456-468, 2022.

[19] A. Singh and P. Kumar, "Solar Power in Smart Surveillance Systems," *Renewable Energy*, vol. 210, pp. 123-134, 2023.

[20] D. Roy, et al., "Energy Harvesting for Edge Computing in Smart Homes," *Journal of Renewable Energy Research*, vol. 12, no. 3, pp. 678-689, 2022.

[21] M. Alam, et al., "Blockchain-Based Solutions for IoT Data Security," *Blockchain Journal*, vol. 2, no. 1, pp. 23-34, 2023.

[22] R. Patel and V. Sharma, "Optimizing AI Models for Edge Devices," *IEEE Transactions on Neural Networks and Learning Systems*, vol. 34, no. 2, pp. 456-467, 2022.

[23] S. Zhang, R. Chen, and D. Li, "Edge-enabled motion detection using IR array sensors and cloud integration," *IEEE Internet of Things Journal*, vol. 14, no. 3, pp. 1[illegible]5-1258, Mar. 2023.

[24] H. Wang, K. Liu, and P. Zhang, "High-precision motion detection using Time-of-Flight sensors with cloud messaging integration," *IEEE Sensors Journal*, vol. 22, no. 8, pp. 7856-7869, Apr. 2023.

[25] M. Patel, A. Johnson, and T. Brown, "Real-time object detection and motion tracking on Jetson Nano using YOLOv5," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 33, no. 5, pp. 2234-2247, M[illegible] 2023.

[26] Y. Kim, J. Park, and S. Lee, "Dual-sensor approach for robust motion detection using mm Wave and thermal imaging," *IEEE Access*, vol. 11, pp. 45678-45691, Jun. 2023.