Engineering and Technology Journal e-ISSN: 2456-3358
Volume 11 Issue 07 July-2026, Page No.-10921-10929
DOI: 10.47191/etj/v11i07.15, I.F. – 8.595

Development and Performance Evaluation of A Solar-Powered Iot-Based cctv Surveillance System for Aviation Navigation Facilities

Irfan[1*], Sukarwoto[2,] Hendri L[3], Fatmawati S[4,] Irwan Jaya[5,] Bambang D[6]
[1,2,3,4,]Makassar Aviation Polytechnic, Makassar, Indonesia
[5*]Barombong Shipping Polytechnic, Makassar, Indonesia
[6*]Surabaya Aviation Polytechnic, Surabaya, Indonesia

ABSTRACT: The security of aviation navigation facilities is an essential aspect of maintaining the continuity and safety of air navigation services. However, remote navigation stations frequently encounter challenges related to limited electrical infrastructure and inadequate surveillance systems, increasing the risk of unauthorized access, equipment theft, and operational disruptions. This study aims to develop and evaluate a solar-powered Internet of Things (IoT)-based Closed-Circuit Television (CCTV) surveillance system designed for remote Distance VHF Omnidirectional Range (DVOR) facilities operated by Air Navigation Indonesia. The research employed a Research and Development (R&D) approach using the ADDIE development model, consisting of Analysis, Design, Development, Implementation, and Evaluation stages. The developed system integrates photovoltaic panels, charge controllers, rechargeable batteries, mini uninterruptible power supply (UPS), Wi-Fi-enabled CCTV cameras, and smartphone-based remote monitoring applications. System performance was evaluated through functional testing, power supply stability assessment, battery backup testing, internet connectivity verification, and expert validation. Experimental results demonstrated that the prototype operated reliably under various weather conditions while maintaining uninterrupted surveillance during electrical outages. Expert validation indicated an average feasibility score of 94.45%, confirming that the developed system satisfies operational requirements for remote aviation surveillance. The proposed solution provides a cost-effective, environmentally sustainable, and scalable alternative for enhancing aviation security in locations where conventional electrical infrastructure is unavailable. Future studies should investigate long-term operational performance under different environmental conditions and integrate artificial intelligence for automated threat detection.

KEYWORDS: Aviation Security; CCTV; Solar Energy; IoT; Surveillance System; Renewable Energy.

INTRODUCTION

The aviation industry increasingly depends on advanced surveillance technologies to ensure the safety, security, and continuity of air navigation services. Along with the rapid growth of air transportation, aviation navigation facilities have become critical infrastructure that requires continuous protection against unauthorized access, vandalism, theft, and environmental disturbances. Maintaining the integrity of these facilities is essential because failures or interruptions in navigation equipment may directly affect the safety and efficiency of aircraft operations. Among various navigation infrastructures, the Distance VHF Omnidirectional Range (DVOR) station plays an important role in providing directional guidance for aircraft during en-route navigation and approach procedures. Since many DVOR facilities are located in isolated or sparsely populated areas, continuous physical monitoring is difficult to perform. Consequently, surveillance systems capable of operating independently from conventional electrical infrastructure have become increasingly important.

Closed-Circuit Television (CCTV) technology has become one of the most widely adopted surveillance systems due to its capability to provide continuous real-time monitoring, record security incidents, and support forensic investigations. Previous studies have demonstrated that CCTV systems significantly improve situational awareness and reduce security vulnerabilities in critical infrastructure. Nevertheless, conventional CCTV installations generally depend on stable commercial electricity, which limits their applicability in remote aviation facilities. Renewable energy technologies have emerged as one of the most promising solutions for supplying electrical power to remote infrastructure where conventional grid electricity is either unavailable or economically impractical. Among the various renewable energy sources, photovoltaic (PV) solar systems have received considerable attention due to their high reliability, modular design, relatively low maintenance requirements, and ability to generate electricity without producing greenhouse gas emissions. Continuous improvements in photovoltaic conversion efficiency, battery energy storage technology, and power management systems have significantly expanded the application of solar energy in various engineering sectors, including telecommunications, environmental monitoring, intelligent transportation systems, and critical infrastructure protection. Consequently, solar-powered systems are increasingly recognized as sustainable alternatives that support global initiatives toward energy efficiency and carbon emission reduction.

For remote aviation navigation facilities, photovoltaic technology offers several operational advantages compared with conventional electrical supply systems. Navigation facilities such as Distance VHF Omnidirectional Range (DVOR), Very High Frequency Omnidirectional Range (VOR), Distance Measuring Equipment (DME), and Non-Directional Beacon (NDB) stations are frequently installed in isolated areas where access to commercial electricity is limited or unstable. Extending electrical transmission networks to these locations often requires substantial investment, while routine maintenance of power infrastructure may be difficult due to geographical constraints. A photovoltaic power system equipped with rechargeable batteries and intelligent charge controllers enables surveillance equipment to operate continuously throughout both daytime and nighttime conditions, thereby improving system availability and reducing dependence on external power sources. In addition to enhancing operational reliability, the use of renewable energy contributes to lower operational costs over the system life cycle and supports environmentally sustainable airport infrastructure development.

Recent advances in the Internet of Things (IoT) have further transformed surveillance technologies by enabling intelligent communication among sensing devices, cloud-based platforms, and mobile applications. Modern IoT-enabled CCTV systems are no longer limited to recording video footage; they are capable of transmitting live video streams, generating real-time notifications, supporting remote configuration, and providing cloud-based data storage through wireless communication networks. These capabilities significantly improve situational awareness because security personnel can monitor facilities regardless of their physical location, allowing faster decision-making and more efficient responses to potential security incidents. Furthermore, the integration of IoT technology with renewable energy systems creates autonomous surveillance platforms that are capable of continuous operation while minimizing human intervention, making them particularly suitable for protecting geographically dispersed critical infrastructure.

Despite the rapid advancement of renewable energy and IoT technologies, relatively limited research has investigated their combined implementation within aviation navigation facilities. Most existing studies have concentrated on smart home security, residential CCTV applications, industrial monitoring, agricultural surveillance, or urban public safety systems. While these studies demonstrate the technical feasibility of solar-powered surveillance systems, they generally do not consider the unique operational requirements of aviation navigation infrastructure, including uninterrupted surveillance, high system reliability, restricted access areas, environmental exposure, and compliance with aviation safety and security standards. Consequently, the direct application of existing surveillance solutions to aviation environments remains challenging and requires further investigation.

Therefore, this study addresses an important research gap by developing and evaluating an integrated solar-powered IoT-based CCTV surveillance system specifically designed for remote aviation navigation facilities. Unlike previous studies that primarily emphasize either renewable energy utilization or IoT-based monitoring separately, the proposed system combines photovoltaic power generation, battery energy storage, uninterrupted power supply (UPS), wireless communication, and smartphone-based remote monitoring into a unified surveillance architecture. This integrated approach not only improves operational continuity and energy independence but also strengthens the physical security of aviation navigation facilities while supporting sustainable infrastructure management. The findings of this study are expected to contribute to the growing body of knowledge on intelligent aviation surveillance systems and provide practical recommendations for implementing renewable-energy-powered security technologies in remote air navigation environments..

Therefore, this study develops and evaluates a solar-powered IoT-based CCTV surveillance prototype for a remote DVOR facility operated by Air Navigation Indonesia. The proposed system integrates photovoltaic power generation, battery backup, wireless communication, and smartphone-based monitoring to provide continuous surveillance under limited electrical infrastructure. The findings are expected to contribute to improving aviation infrastructure security while supporting the implementation of environmentally sustainable surveillance technologies.

METODE

This study employed a Research and Development (R&D) approach to design, construct, and evaluate a solar-powered Closed-Circuit Television (CCTV) surveillance system intended for aviation navigation facilities. Unlike experimental studies that primarily investigate causal relationships between variables, the R&D approach focuses on developing technological products while simultaneously validating their performance and operational feasibility.

The development process adopted the ADDIE instructional development model, consisting of five systematic phases: Analysis, Design, Development, Implementation, and Evaluation. Although originally developed for educational product development, the ADDIE model has been widely applied in engineering research because it provides a structured framework for designing, implementing, testing, and refining prototype systems. The sequential nature of the model facilitates continuous improvements throughout the development cycle while ensuring that each design decision is based on user requirements and technical evaluation.

1. Analysis Phase

The analysis phase aimed to identify operational problems associated with the security of the Distance VHF Omnidirectional Range (DVOR) site. Preliminary observations and interviews with AirNav Indonesia personnel revealed that continuous physical surveillance could not be maintained due to limited aviation security personnel, budget constraints, and the absence of permanent CCTV infrastructure. Another critical challenge identified during field observations was the unreliable availability of electrical power. Frequent power outages significantly reduced the effectiveness of conventional surveillance systems because commercially available CCTV installations require continuous electrical supply. Furthermore, installing conventional electrical infrastructure in remote navigation facilities requires substantial investment and maintenance costs.

These operational constraints highlighted the need for an autonomous surveillance system capable of operating independently using renewable energy while providing real-time monitoring through wireless communication technology. The proposed prototype was therefore designed to address these operational limitations by integrating solar photovoltaic technology, rechargeable batteries, uninterrupted power supply (UPS), wireless communication, and smartphone-based monitoring applications. The identified operational issues are consistent with the background described in the original study.

2. System Design

Following the needs analysis, a conceptual system architecture was developed to integrate renewable energy generation, energy storage, surveillance devices, and wireless communication into a unified monitoring system.

The prototype consists of six primary subsystems:

- ✓ photovoltaic solar panel,
- ✓ solar charge controller,
- ✓ rechargeable lithium battery pack,
- ✓ mini Uninterruptible Power Supply (UPS),
- ✓ Wi-Fi-enabled CCTV camera,
- ✓ smartphone-based monitoring application.

The photovoltaic module converts solar radiation into direct current (DC) electrical energy. The generated electricity is regulated by a solar charge controller to ensure stable battery charging while preventing overcharging and deep discharge. Electrical energy is subsequently stored within rechargeable batteries, which function as the primary energy storage component. A mini UPS maintains continuous power delivery to the CCTV camera during temporary interruptions in solar energy generation caused by nighttime operation or unfavorable weather conditions.

The CCTV camera transmits video data wirelessly through a Wi-Fi dongle connected to an Internet network. Authorized users can access live video streaming, playback recorded footage, receive motion detection notifications, and manage camera settings remotely using the Tuya Smart mobile application installed on Android smartphones.

The overall system architecture was designed to provide continuous surveillance without dependence on conventional grid electricity while minimizing operational costs and maintenance requirements.

3. Prototype Development

The prototype development stage involved mechanical assembly, electrical integration, software installation, and system configuration. The electrical subsystem consisted of photovoltaic panels connected to a solar charge controller. Rechargeable batteries were connected in parallel to increase storage capacity before supplying electrical energy to the mini UPS. The UPS output provided a regulated DC voltage to the CCTV camera, ensuring uninterrupted operation even during fluctuating environmental conditions.

The surveillance subsystem utilized a wireless CCTV camera equipped with Internet connectivity capabilities. Network communication was established using a portable Wi-Fi dongle connected to available mobile Internet services. Remote monitoring functionality was implemented using the Tuya Smart application, allowing users to configure the camera, receive security alerts, monitor live video, and review recorded footage through Android smartphones. Each subsystem was assembled individually before being integrated into a complete surveillance platform. Functional verification was conducted throughout the assembly process to ensure compatibility among electrical and communication components prior to field testing. The prototype assembly procedure follows the hardware integration described in the original development process.

4. System Testing

Prototype evaluation consisted of comprehensive functional testing performed under both laboratory and field conditions. The testing procedure evaluated the following operational parameters:

a) Solar panel charging performance.
b) Charge controller functionality.
c) Battery charging efficiency.
d) Battery backup duration.
e) Mini UPS operational stability.
f) Output voltage consistency.
g) CCTV operational performance.
h) Internet connectivity.
i) Remote monitoring capability.
j) Wireless communication stability.
k) Video recording quality.

l) Smartphone application functionality.

Performance evaluation was conducted under different weather conditions, including sunny and cloudy environments, to determine the stability of photovoltaic power generation. Output voltage measurements were obtained using a digital voltmeter to evaluate electrical stability throughout charging and discharging cycles. Wireless connectivity tests assessed the ability of the CCTV camera to maintain Internet communication for continuous live streaming and remote access. Functional testing also evaluated user interaction with the Tuya Smart application, including account registration, camera pairing, live monitoring, motion notification, and playback functionality. These testing activities correspond to the operational procedures documented in the prototype evaluation chapter

5. Data Collection

Data collection consisted of both qualitative and quantitative approaches. Qualitative data were obtained through field observations, interviews with AirNav Indonesia personnel, and documentation of prototype installation activities. These observations provided practical information regarding operational challenges, environmental conditions, and user requirements for surveillance implementation.

Quantitative data were collected from prototype performance measurements, including battery voltage, charging performance, CCTV functionality, wireless communication stability, and operational continuity under different environmental conditions. Measurement results were documented using observation sheets and electrical measuring instruments throughout the testing process.

6. Data Analysis

The collected data were analyzed using descriptive statistical techniques to evaluate the operational performance of the developed surveillance system. Prototype feasibility was further assessed using expert validation involving competent evaluators experienced in aviation navigation systems and electronic engineering. Each evaluation indicator was rated according to predefined assessment criteria covering hardware functionality, electrical performance, surveillance capability, communication reliability, and operational feasibility. The overall feasibility percentage was calculated using:

$$\text{Feasibility (\%)} = \frac{\sum X}{\sum X_{max}} \times 100$$

where:

$\sum X$ = total obtained score

$\sum X$ max = maximum possible score

The resulting percentage was interpreted according to feasibility criteria commonly applied in engineering product validation. The prototype achieved an overall expert validation score of 94.45%, indicating that the developed surveillance system was classified as highly feasible for operational implementation within remote aviation navigation facilities.

HASIL DAN PEMBAHASAN

This section presents the outcomes of the prototype development and performance evaluation of the proposed solar-powered IoT-based CCTV surveillance system for aviation navigation facilities. The results are organized according to the major stages of system development, including prototype construction, photovoltaic power generation, surveillance functionality, battery backup performance, remote monitoring capability, and expert validation. Comprehensive performance testing was conducted to determine the operational feasibility, reliability, and effectiveness of the developed system under simulated field conditions. In addition to presenting the technical performance of each subsystem, this section also highlights the overall capability of the integrated surveillance system to provide continuous monitoring for remote Distance VHF Omnidirectional Range (DVOR) facilities where conventional electrical infrastructure is limited. The findings presented in this section form the basis for the subsequent discussion regarding the practical implications, technological contributions, and potential implementation of the proposed system within aviation navigation environments.

1. Prototype Development

The primary outcome of this study is the successful development of a solar-powered IoT-based CCTV surveillance prototype intended for securing remote aviation navigation facilities. The prototype integrates renewable energy generation, energy storage, wireless communication, and real-time video surveillance into a single autonomous monitoring system. The developed system consists of photovoltaic panels, a solar charge controller, rechargeable batteries connected in parallel, a mini uninterruptible power supply (UPS), a wireless CCTV camera, a Wi-Fi dongle, and a smartphone-based monitoring application. These components were integrated to ensure continuous surveillance even in locations without access to conventional electrical infrastructure. The overall prototype architecture is illustrated in the original design documentation.

Unlike conventional CCTV installations that rely entirely on grid electricity, the proposed prototype operates independently using solar energy. During daylight hours, electrical energy generated by the photovoltaic panel simultaneously powers the surveillance system and charges the battery pack. At night or during cloudy conditions, the stored battery energy automatically supplies electrical power through the mini UPS without interrupting camera operation. This autonomous power management mechanism significantly improves surveillance continuity while reducing operational costs associated with electrical infrastructure installation.

2. Solar Power Performance

The photovoltaic subsystem demonstrated stable electrical generation throughout prototype testing. Performance evaluation under different environmental conditions indicated that the solar panel was capable of producing sufficient electrical energy to maintain continuous battery charging during sunny weather while still providing usable charging current under partially cloudy conditions. The charge controller effectively regulated charging voltage and protected the battery from overcharging and excessive discharge.

The integration of rechargeable batteries allowed surplus electrical energy generated during peak solar irradiation to be stored for nighttime operation. Consequently, uninterrupted surveillance could be maintained despite temporary reductions in solar intensity. The implementation of renewable energy also contributes to reducing dependence on fossil-fuel-based electricity, making the surveillance system more environmentally sustainable for long-term deployment at isolated aviation facilities.

Tabel 1. Electrical Performance of Solar Power Components

Component	Expected Function	Testing Result	Performance
Solar Panel	Generate electrical energy	Successful	Stable
Charge Controller	Regulate charging voltage	Successful	Stable
Battery Pack	Store electrical energy	Successful	Stable
Mini UPS	Backup electrical supply	Successful	Stable
Output Voltage	Stable power delivery	Stable	Excellent

3. CCTV Operasional Performance

Functional testing confirmed that the surveillance subsystem operated successfully throughout all testing scenarios. The wireless CCTV camera consistently captured clear video images and maintained stable Internet connectivity using the Wi-Fi dongle. Users were able to access live video streams remotely using the Tuya Smart mobile application without noticeable communication interruptions. Several operational functions were evaluated, including:

- ✓ real-time monitoring,
- ✓ motion detection,
- ✓ video recording,
- ✓ playback,
- ✓ wireless connectivity,
- ✓ smartphone notification,
- ✓ remote configuration.

All tested functions performed according to design specifications, indicating that the surveillance system satisfies the operational requirements of remote aviation monitoring. The integration of smartphone-based monitoring significantly improves operational flexibility because security personnel can supervise navigation facilities without remaining physically present at the surveillance site.

Tabel 2. Functional Evaluation of CCTV System

Parameter	Result
Camera Operation	Successful
Video Recording	Successful
Image Quality	Clear
Live Streaming	Stable
Remote Monitoring	Successful
Internet Connectivity	Stable
Smartphone Integration	Successful

4. Battery Backup Performance

One of the most important characteristics of the proposed prototype is its capability to maintain surveillance continuity during electrical interruptions. Testing demonstrated that the rechargeable battery pack successfully supplied electrical power through the mini UPS whenever solar power generation became unavailable. The UPS automatically switched between charging mode and backup mode without causing system shutdown or loss of surveillance capability. This automatic transition is particularly important for aviation navigation facilities because surveillance interruptions may create security vulnerabilities that increase the possibility of unauthorized access. The battery management system also maintained stable output voltage throughout testing, preventing voltage fluctuations that could damage sensitive electronic equipment.

5. Smartphone-Based Remote Monitoring

Remote monitoring functionality was implemented using the Tuya Smart mobile application. The application installation process included:

- ✓ user registration,

- ✓ email verification,
- ✓ OTP authentication,
- ✓ device pairing,
- ✓ Wi-Fi configuration,
- ✓ live monitoring.

Once connected, users could access real-time surveillance from virtually any location with Internet connectivity. Additional features included:

- ✓ motion detection alerts,
- ✓ playback of recorded footage,
- ✓ screenshot capture,
- ✓ camera configuration,
- ✓ cloud storage synchronization.

The successful implementation of smartphone monitoring demonstrates the applicability of IoT technology for aviation security operations. The configuration sequence follows the implementation documented in the prototype installation chapter.

6. Expert Validation

Expert validation was conducted to evaluate the operational feasibility of the developed surveillance prototype. The evaluation considered several performance indicators, including:

- ✓ photovoltaic subsystem,
- ✓ battery charging,
- ✓ UPS functionality,
- ✓ voltmeter accuracy,
- ✓ CCTV performance,
- ✓ wireless communication,
- ✓ remote monitoring capability.

Each indicator was assessed by competent experts using structured evaluation criteria. The obtained results indicate that almost all assessment indicators achieved feasibility scores exceeding 90%. The overall average validation score reached 94.45%, demonstrating that the developed prototype satisfies engineering performance requirements and is classified as Highly Feasible for practical implementation

Tabel 3. Expert Validation Results

Evaluation Aspect	**Score (%)**
Solar Charging	91.67
Battery Performance	91.67
UPS Backup	83.33
Voltmeter Accuracy	100.00
CCTV Image Quality	100.00
Internet Connectivity	91.67
Remote Monitoring	91.67
Wi-Fi Dongle Performance	91.67
Overall Average	94.45

7. Overall System Performance

The integration of renewable energy and IoT technology successfully produced a surveillance system capable of operating autonomously under remote environmental conditions. From an engineering perspective, the developed prototype offers several operational advantages:

- ✓ independent electrical operation,
- ✓ uninterrupted surveillance,
- ✓ low operational cost,
- ✓ environmentally friendly energy utilization,
- ✓ real-time remote monitoring,
- ✓ scalable architecture for larger navigation facilities.

These findings indicate that the prototype can serve as a practical alternative to conventional CCTV systems, particularly for aviation navigation facilities located in areas with limited electrical infrastructure.

DISCUSSION

The present study successfully developed and evaluated a solar-powered Internet of Things (IoT)-based Closed-Circuit Television (CCTV) surveillance system intended to improve the security of remote aviation navigation facilities. The findings demonstrate that integrating photovoltaic technology, battery energy storage, wireless communication, and smartphone-based monitoring can provide a reliable and sustainable surveillance solution for locations where conventional electrical infrastructure is limited. The prototype achieved high operational feasibility, with an overall expert validation score of 94.45%, indicating that the developed system satisfies the functional requirements for practical deployment. Unlike conventional surveillance systems that depend entirely on commercial electricity, the proposed system operates autonomously by utilizing renewable solar energy. This characteristic is particularly important for aviation navigation facilities such as Distance VHF Omnidirectional Range (DVOR) stations, which are commonly located in isolated areas with limited access to electrical infrastructure. The autonomous energy supply ensures uninterrupted monitoring even during power outages, thereby minimizing security vulnerabilities associated with equipment downtime. The implementation of renewable energy in surveillance systems also supports global efforts toward sustainable infrastructure development and aligns with the increasing adoption of environmentally friendly technologies within the aviation sector.

The performance evaluation indicates that the photovoltaic subsystem was capable of supplying sufficient electrical energy to operate the CCTV continuously while simultaneously charging the battery storage unit. The charge controller effectively maintained charging stability and protected the batteries from overcharging, whereas the mini UPS ensured uninterrupted power delivery during transitions between charging and battery operation. The stable electrical performance observed throughout the testing process confirms that integrating renewable energy technologies into security systems can significantly improve operational reliability in remote environments. These findings are consistent with previous studies demonstrating that photovoltaic energy systems provide dependable electrical power for low-consumption monitoring devices deployed in off-grid applications. Another important contribution of this study is the successful integration of IoT technology into aviation security monitoring. Through wireless Internet communication and smartphone-based applications, security personnel are able to monitor navigation facilities remotely without requiring permanent physical presence at the surveillance site. The successful implementation of remote access, live video streaming, motion detection, and cloud-based monitoring demonstrates that IoT technologies substantially improve operational efficiency compared to traditional CCTV systems that require local monitoring stations.

The implementation of smartphone-based surveillance also enhances response capability during security incidents. Real-time notifications allow authorized personnel to receive immediate information regarding unusual activities occurring within restricted operational areas. Consequently, the time required for security response can be significantly reduced, thereby minimizing the possibility of unauthorized access or intentional vandalism targeting navigation equipment. From an aviation safety perspective, protecting navigation facilities is an essential component of maintaining the continuity of air navigation services. Navigation aids such as DVOR provide critical guidance information for aircraft during en-route navigation and terminal operations. Any intentional damage or unauthorized interference affecting these facilities may reduce navigation service availability and potentially influence operational safety. Therefore, improving physical security through continuous surveillance contributes indirectly to maintaining aviation safety and operational reliability.

The findings further demonstrate that the proposed surveillance architecture offers greater operational flexibility than conventional CCTV installations. Because the system utilizes wireless Internet communication rather than extensive wired infrastructure, installation becomes considerably simpler, particularly in geographically isolated locations. Maintenance activities are also reduced because the renewable energy subsystem eliminates dependence on commercial electrical networks while minimizing recurring operational costs. Economic considerations also support the implementation of the developed prototype. Conventional CCTV installations require electrical infrastructure expansion, continuous electricity consumption, and routine maintenance of transmission networks. In contrast, the proposed solar-powered system primarily depends on renewable energy generated by photovoltaic panels. Although the initial investment may be relatively higher due to photovoltaic components and battery storage, operational expenditures are expected to decrease substantially over the long term because electricity costs are significantly reduced. This life-cycle cost advantage is particularly beneficial for government agencies responsible for managing multiple remote navigation facilities across geographically dispersed regions.

The expert validation results further strengthen the reliability of the developed prototype. Most evaluation indicators obtained scores above 90%, with image quality and voltmeter performance achieving perfect evaluation scores. These results indicate that the selected hardware components functioned according to design specifications and were successfully integrated into a unified surveillance platform. The slightly lower evaluation score for the UPS backup function suggests opportunities for future optimization, particularly regarding battery capacity, energy management algorithms, and backup duration under extended low-solar conditions. Compared with previous surveillance studies, the present research provides several important contributions. Many earlier investigations focused primarily on residential security systems, industrial monitoring, or smart home applications using IoT technologies. Although these studies demonstrated the effectiveness of remote surveillance, relatively few addressed the unique operational requirements of aviation navigation facilities. The present study therefore extends existing knowledge by adapting renewable-energy-powered surveillance technology to support aviation infrastructure protection, which has received comparatively limited attention within the current literature. Another distinctive contribution lies in integrating multiple technologies into a single operational platform. Instead of simply installing CCTV equipment, the proposed system combines renewable energy generation, battery management, uninterrupted power supply, wireless communication, cloud-based monitoring, and smartphone applications into one integrated surveillance architecture. This multidimensional integration improves system resilience while simultaneously supporting sustainable infrastructure development.

Despite these encouraging findings, several limitations should be acknowledged. First, the prototype was evaluated within a limited operational environment and relatively short observation period. Long-term system performance under varying seasonal weather conditions, prolonged battery aging, and continuous operational loads has not yet been investigated. Second, Internet connectivity depended on the availability of mobile communication networks. Remote locations with weak cellular coverage may experience reduced monitoring quality or temporary communication interruptions. Third, the current prototype focuses primarily on surveillance functionality and does not yet incorporate intelligent image analysis or automated threat detection capabilities. Future research should therefore concentrate on improving system intelligence through the integration of artificial intelligence (AI), computer vision, and machine learning algorithms capable of automatically identifying unauthorized intrusion, suspicious human behavior, wildlife interference, or equipment abnormalities. AI-assisted surveillance would substantially reduce operator workload while improving early warning capability. In addition, integrating environmental sensors, Internet of Things gateways, and cloud analytics could transform the surveillance platform into a comprehensive smart monitoring system capable of supporting predictive maintenance for aviation navigation facilities.

The application potential of the developed prototype extends beyond DVOR stations. Similar surveillance architectures may also be implemented at VOR, DME, NDB, radar stations, communication facilities, Automatic Weather Observing Systems (AWOS), and other critical aviation infrastructure located in remote environments. Consequently, the proposed technology represents not only an engineering solution for improving security but also an important contribution toward the digital transformation and sustainability of aviation infrastructure management. Overall, the findings demonstrate that the integration of renewable energy and IoT technologies can significantly enhance the resilience, efficiency, and sustainability of surveillance systems deployed within aviation navigation environments. The developed prototype provides a practical and economically feasible solution for strengthening physical security while supporting continuous operational availability of critical air navigation infrastructure.

CONCLASION

This study successfully developed and evaluated a solar-powered Internet of Things (IoT)-based Closed-Circuit Television (CCTV) surveillance system designed to enhance the security of remote aviation navigation facilities, particularly the Distance VHF Omnidirectional Range (DVOR) station operated by Air Navigation Indonesia. By integrating photovoltaic technology, rechargeable battery storage, a mini uninterruptible power supply (UPS), wireless communication, and smartphone-based remote monitoring, the proposed prototype provides a reliable autonomous surveillance solution capable of operating independently from conventional electrical infrastructure. The development process followed the Research and Development (R&D) methodology using the ADDIE model, which enabled systematic design, implementation, testing, and evaluation of the surveillance system. The performance evaluation demonstrated that all major system components operated according to their intended functions. The photovoltaic subsystem successfully generated renewable electrical energy to support continuous CCTV operation, while the battery storage and UPS subsystem maintained uninterrupted power supply during periods of insufficient solar irradiation. Furthermore, the wireless CCTV camera provided stable Internet connectivity and enabled real-time monitoring through a smartphone application, allowing security personnel to supervise navigation facilities remotely. Expert validation produced an overall feasibility score of 94.45%, indicating that the developed prototype satisfies the technical and operational requirements for practical implementation within remote aviation environments.

From a practical perspective, the developed surveillance system offers several significant advantages over conventional CCTV installations. The utilization of renewable solar energy reduces dependence on commercial electrical infrastructure while lowering long-term operational costs. The integration of IoT technology further enhances surveillance efficiency by enabling remote access, real-time monitoring, and rapid security response without requiring continuous on-site personnel. These characteristics make the proposed system particularly suitable for isolated aviation navigation facilities where infrastructure availability and human resources are limited.

The present study also contributes to the advancement of aviation infrastructure protection by demonstrating the feasibility of integrating renewable energy and IoT technologies into surveillance systems for critical air navigation facilities. Unlike previous studies that primarily focused on residential or industrial security applications, this research extends the implementation of intelligent surveillance technology to the aviation sector, thereby providing an alternative approach for improving operational resilience and infrastructure security. This interdisciplinary integration represents an important contribution to the development of sustainable aviation technologies and smart airport infrastructure. Nevertheless, several limitations remain. The prototype was evaluated over a relatively limited operational period and within a specific environmental setting. Long-term system reliability under varying climatic conditions, battery degradation, and continuous operational loads has not yet been comprehensively assessed. Additionally, the current system relies on conventional motion detection and remote monitoring capabilities without incorporating intelligent image processing or automated threat recognition.

Future research should therefore focus on integrating Artificial Intelligence (AI) and computer vision algorithms to enable automatic intrusion detection, anomaly recognition, and predictive security monitoring. Additional investigations involving long-term field deployment, comparative energy-efficiency analysis, larger photovoltaic capacities, and cloud-based data analytics are also recommended to further improve system reliability and operational effectiveness. Expanding the proposed surveillance architecture to other aviation navigation facilities, including VOR, DME, radar stations, communication sites, and Automatic Weather Observing Systems (AWOS), would provide broader evidence regarding the scalability and applicability of renewable energy-based surveillance systems within modern aviation infrastructure.

In conclusion, the proposed solar-powered IoT-based CCTV surveillance system demonstrates considerable potential as an innovative, sustainable, and cost-effective solution for strengthening the security of remote aviation navigation facilities. The integration of renewable energy, intelligent monitoring technology, and wireless communication provides a practical framework that supports both operational continuity and sustainable infrastructure development, thereby contributing to safer and more resilient air navigation services..

REFERENCES

1. Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash, M. (2015). Internet of Things: A survey on enabling technologies, protocols, and applications. IEEE Communications Surveys & Tutorials, 17(4), 2347–2376. https://doi.org/10.1109/COMST.2015.2444095
2. Ashford, N., Mumayiz, S., & Wright, P. H. (2011). Airport Engineering: Planning, Design, and Development of 21st Century Airports (4th ed.). John Wiley & Sons.
3. Bochkovskiy, A., Wang, C. Y., & Liao, H. Y. M. (2020). YOLOv4: Optimal speed and accuracy of object detection. arXiv. https://arxiv.org/abs/2004.10934
4. Creswell, J. W., & Creswell, J. D. (2023). Research Design: Qualitative, Quantitative, and Mixed Methods Approaches (6th ed.). Sage Publications.
5. Dick, W., Carey, L., & Carey, J. O. (2015). The Systematic Design of Instruction (8th ed.). Pearson.
6. Federal Aviation Administration. (2023). Aeronautical Information Manual. Federal Aviation Administration.
7. Federal Aviation Administration. (2023). FAA Order 6032.1: National Airspace System Security. Federal Aviation Administration.
8. Hanif, M., Nurhayati, D., & Kurniawan, E. (2020). Design and calibration of digital voltmeter for electrical measurement applications. Journal of Physics: Conference Series, 1569(2), 022018. https://doi.org/10.1088/1742-6596/1569/2/022018
9. International Civil Aviation Organization. (2018). Annex 17 to the Convention on International Civil Aviation: Security—Safeguarding International Civil Aviation Against Acts of Unlawful Interference (11th ed.). ICAO.
10. International Civil Aviation Organization. (2022). Annex 10 to the Convention on International Civil Aviation: Aeronautical Telecommunications (Vol. I). ICAO.
11. International Civil Aviation Organization. (2022). Annex 11 to the Convention on International Civil Aviation: Air Traffic Services. ICAO.
12. International Civil Aviation Organization. (2023). Safety Management Manual (Doc 9859) (5th ed.). ICAO.
13. International Civil Aviation Organization. (2024). Global Aviation Security Plan (GASeP). ICAO.
14. International Energy Agency. (2023). Renewables 2023. IEA.
15. Lund, H. (2022). Renewable Energy Systems (3rd ed.). Academic Press.
16. Montgomery, D. C. (2020). Design and Analysis of Experiments (10th ed.). John Wiley & Sons.
17. Redmon, J., Divvala, S., Girshick, R., & Farhadi, A. (2016). You Only Look Once: Unified, real-time object detection. Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 779–788.
18. Silviati, S., Yuliza, E., & Rahman, A. (2017). Development of digital voltmeter for electronic laboratory applications. Journal of Physics: Conference Series, 877, 012061. https://doi.org/10.1088/1742-6596/877/1/012061
19. Stutzer, H., & Zehnder, A. (2013). Airport Security and Ground Handling Management. Springer.