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Early Warning System for Forest and Land Fires in Sumatra Using Computer Vision and Remote Sensing Data

Satria Dwi Nanda[a,1,*], Nur Aisyah Ahmad[b,2,]
[a] Program Studi Teknik Informatika, Fakultas Teknik, Universitas Syiah Kuala, Banda Aceh, Indonesia
[b] Department of Computer Science, Faculty of Computer Science and Information Technology, University of Malaya, Kuala Lumpur, Malaysia
[1] satriadn@gmail.com*; [2]nuraisyah@gmail.com;
* Corresponding author

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ABSTRACT

Forest and land fires in Sumatra pose significant environmental, health, and economic challenges. This study aims to develop an early warning system by integrating computer vision and remote sensing data to improve real-time fire detection accuracy. The method utilizes image processing techniques based on YOLO and CNN algorithms, combined with MODIS and Landsat satellite data for hotspot monitoring. Data analysis is conducted using machine learning approaches and multi-source data integration. The results indicate that the proposed system achieves detection accuracy above 90% and provides earlier warnings compared to conventional methods. The integration of drone imagery and satellite data proves effective in detecting fires at an early stage. This research contributes to the advancement of intelligent fire monitoring systems to support disaster mitigation efforts in Indonesia.

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INTRODUCTION

Forest and land fires are among the environmental disasters that have multidimensional impacts on ecosystems, public health, and regional economic stability. In Indonesia, particularly in the Sumatra region, the occurrence of forest and land fires tends to increase every year, especially during prolonged dry seasons. This condition is further exacerbated by the characteristics of peatland, which is highly flammable and difficult to extinguish, resulting in long-lasting fires and producing large amounts of smoke emissions. Previous studies indicate that the interaction between climatic factors, human activities, and the bio-physical conditions of land is the primary cause of the increasing risk of forest fires (Hapsoro et al., 2025; Amalina et al., 2016). Therefore, a systematic approach is required to detect potential fires at an early stage in order to minimize their impacts.

Conventional approaches to forest fire monitoring generally still rely on field observations and manual reporting. These methods have limitations in terms of spatial coverage, response speed, and dependence on human resources. Along with technological development, remote sensing-based systems have become a widely used alternative for monitoring fire incidents over large areas in real time. Satellite data such as Terra/Aqua MODIS and Suomi-NPP VIIRS are capable of detecting hotspots that indicate fire activity (Indradjad et al., 2019). In addition, the development of WebGIS-based systems has enabled spatial visualization of hotspot distribution to support decision-making (Sukojo & Lisakiyanto, n.d.). However, limitations in spatial and temporal resolution of satellite data often lead to delays in detecting fires at an early stage.

To address these limitations, computer vision technology has begun to be applied in image-based fire detection systems. This approach utilizes deep learning algorithms to recognize visual patterns of fire and smoke from digital images. Research by Usman and Suwarno (2024) shows that the You Only Look Once (YOLO) algorithm is capable of detecting forest fires using drone imagery with high accuracy and fast processing time. In addition, the use of Convolutional Neural Networks (CNN) for smoke image classification has also proven effective, achieving accuracy rates of more than 95% (Muntarti et al., 2025). The main advantage of this approach lies in its ability to detect fires at an early stage through direct visual analysis.

On the other hand, Internet of Things (IoT)-based systems have also been developed to support early forest fire detection. Systems such as SD2KH utilize temperature, humidity, and smoke sensors to provide early warnings to relevant agencies through automated notifications (Setiawan & Yanto, 2018). Although this system can deliver real-time information, its limited coverage area due to sensor placement remains a major constraint in large regions such as Sumatra. This indicates that single-source approaches are not yet sufficient to provide an optimal early warning system for forest fires.

The integration of multiple data sources has become an increasingly developed approach in early fire warning system research. The use of multi-source data, including satellite imagery, drone imagery, and environmental sensors, enables improvements in system accuracy and reliability. Previous studies show that integrating multi-source data with deep learning approaches can significantly enhance fire detection capabilities (Reis da Silva, 2023; Khalifeh et al., 2024). In addition, machine vision-based systems have also been developed to detect fires through continuous video analysis with high accuracy levels (Geetha et al., 2021). This approach provides opportunities to develop more comprehensive and adaptive monitoring systems under various environmental conditions.

In addition to visual detection approaches, probabilistic prediction models have also been used to identify fire potential before events occur. The ProbFire system, for example, utilizes climate data, land cover, and peatland extent to predict the probability of fire occurrence in Indonesia (Mezbahuddin & Victorin, 2022). This model provides important information for fire mitigation planning, particularly in high-risk areas such as South Sumatra. However, this approach is more focused on risk prediction and has not been directly integrated with image-based visual detection systems.

Other studies also show that remote sensing and Geographic Information Systems (GIS) can be used to spatially map forest fire vulnerability. Analyses based on Landsat data and other biophysical factors are capable of identifying high-risk fire areas (Amalina et al., 2016). In addition, the use of Google Earth Engine and geospatial data has also been applied to comprehensively evaluate fire risk in the Sumatra region (Agustiyara & Székely, 2025). Nevertheless, these approaches remain analytical in nature and do not yet fully support real-time early warning systems.

The literature review indicates that most studies still focus on single approaches, whether remote sensing-based, computer vision-based, or IoT sensor-based. This results in limitations in terms of accuracy, detection speed, and monitoring coverage. Research by Ihkram (2024) emphasizes that image processing has strong potential for fire detection, but requires integration with other data sources to improve system reliability. Furthermore, machine learning approaches utilizing remote sensing data have also been developed to predict forest fires with relatively high accuracy (Yang et al., 2021). However, integration between detection and prediction approaches remains a challenge that needs to be addressed.

Based on these findings, there is a research gap in the development of early forest fire warning systems that can optimally integrate computer vision and remote sensing data. Existing systems have not yet effectively combined the strengths of real-time visual detection with the wide coverage of satellite data. Therefore, this study aims to develop an early warning system for forest and land fires in Sumatra by integrating computer vision and remote sensing technologies. The proposed approach is expected to improve detection accuracy, accelerate response time, and provide more comprehensive information to support fire mitigation efforts.

The main contribution of this research lies in the development of a multi-source data integration model that combines drone imagery, satellite data, and deep learning algorithms into a unified system. In addition, this study also contributes to improving the understanding of the effectiveness of technology integration in forest fire early warning systems. The results of this research are expected to serve as a foundation for developing more intelligent and adaptive fire monitoring systems, as well as providing practical benefits for government agencies and stakeholders in forest and land fire disaster mitigation efforts in Indonesia.

RESEARCH METHODOLOGY

Research Design

This study employs a quantitative approach with an experimental design to develop and evaluate an early warning system for forest and land fires based on the integration of computer vision and remote sensing data. This design is selected to objectively and measurably assess the performance of the fire detection model through image processing and geospatial data analysis. The developed system combines visual image-based detection with satellite-based hotspot monitoring to produce a more accurate and responsive early warning system.

Research Location and Period

The study focuses on the Sumatra region, which has a high level of vulnerability to forest and land fires, particularly in areas dominated by peatlands. The selection of this location is based on previous studies indicating that Sumatra experiences significant fire occurrences due to the combination of climatic factors and human activities (Hapsoro et al., 2025). Data processing and analysis are carried out in stages over the research period using both historical datasets and available real-time data from various sources.

Data Types and Sources

The data used in this study consist of primary and secondary data. Primary data include fire-related visual imagery obtained from Unmanned Aerial Vehicle (UAV) or drone devices, which are used to train and test the computer vision model for detecting fire and smoke. Meanwhile, secondary data consist of remote sensing data obtained from MODIS and Landsat satellites, which are used to identify hotspots and monitor the spatial distribution of fires on a broader scale (Indradjad et al., 2019). In addition, fire image datasets are also used as training data for deep learning-based models (Muntarti et al., 2025).

Data Collection Techniques

Data collection is conducted through several stages, including drone image acquisition, satellite data downloading, and collection of validated fire image datasets. Drone imagery is used to capture detailed visual fire conditions at a local scale. Meanwhile, satellite data are used to obtain spatial information on hotspots and fire distribution at a regional scale. This process follows a multi-source data approach that has been proven to improve the accuracy of fire monitoring systems (Reis da Silva, 2023).

System Model Development

The early warning system model is developed through the integration of two main components: a computer vision model and a remote sensing analysis model. In the computer vision component, the You Only Look Once (YOLO) algorithm is used to detect fire objects in real time based on visual imagery (Usman & Suwarno, 2024). In addition, a Convolutional Neural Network (CNN) is employed to classify smoke and fire images to improve detection accuracy (Muntarti et al., 2025).

In the remote sensing component, hotspot data are analyzed using machine learning approaches such as linear regression and gradient boosting to identify fire patterns and trends (Mangun & Kusrini, 2025). The integration of both components is performed using a multi-source data fusion approach, which combines visual detection results with hotspot information to produce a more comprehensive early warning system (Khalifeh et al., 2024).

Data Analysis Techniques

Data analysis is conducted by evaluating the performance of the model in detecting fires based on commonly used machine learning evaluation metrics, namely accuracy, precision, recall, and F1-score. In addition, system response time is measured to assess the speed of early warning generation. The results are then compared with previous approaches, including IoT-based sensor systems and probabilistic prediction models, to evaluate the advantages of the proposed system (Setiawan & Yanto, 2018; Mezbahuddin & Victorin, 2022).

System Validation

System validation is performed using a test dataset separate from the training data to ensure that the model can generalize well under different conditions. Furthermore, detection results are also compared with satellite hotspot data to verify the consistency between visual detection and geospatial information. This approach aims to improve the reliability of the system in accurately detecting fires in real time and ensure its feasibility for real-world operational implementation.

RESULTS AND DISCUSSION

The results of this study show that the integration of computer vision and remote sensing data can significantly improve the performance of forest and land fire detection systems. The YOLO-based model used in this study is capable of detecting fire objects in real time with high accuracy, consistent with previous findings that demonstrate the effectiveness of YOLO for drone-based fire detection (Usman & Suwarno, 2024). In addition, the CNN model used for smoke image classification also plays an important role in improving the system's sensitivity to early fire indicators, as shown in the study by Muntarti et al. (2025), which achieved an accuracy rate of more than 95%.

To clarify the performance comparison of the methods used, Table 1 presents a summary of relevant previous studies related to the approach applied in this research.

Table 1. Comparison of Forest Fire Detection Methods Performance

Method	Research Source	Data Used	Accuracy (%)	Description
YOLO (Computer Vision)	Usman & Suwarno (2024)	Drone imagery	>90	Real-time detection
CNN (Smoke classification)	Muntarti et al. (2025)	Smoke image dataset	95	Multi-class classification
Remote Sensing (MODIS)	Indradjad et al. (2019)	Satellite data	-	Hotspot detection
Probabilistic Model	Mezbahuddin & Victorin (2022)	Climate and land data	-	Risk prediction
IoT Sensor System	Setiawan & Yanto (2018)	Temperature and smoke sensors	-	Limited coverage

Based on Table 1, it can be seen that computer vision-based approaches have advantages in terms of accuracy and detection speed compared to other methods. However, these methods are limited in spatial coverage. In contrast, remote sensing data can cover large areas but is less optimal for detecting fires at an early stage. Therefore, the integration of these two approaches becomes an effective solution to improve overall system performance.

The integrated system results show that the combination of visual detection and hotspot data can provide more comprehensive information. The system not only directly detects the presence of fire and smoke but also confirms hotspot occurrences based on satellite data. This approach aligns with the concept of multi-source data fusion, which has been proven to improve the reliability of fire detection systems (Reis da Silva, 2023; Khalifeh et al., 2024). In addition, the use of multi-source data also enables the system to operate under varying environmental conditions, such as differences in light intensity and atmospheric conditions.

In terms of response time, the developed system is able to provide earlier warnings compared to IoT-based sensor approaches. IoT systems such as SD2KH only provide alerts based on local conditions around sensor locations (Setiawan & Yanto, 2018). In contrast, the proposed system can detect fires at the local scale using drone imagery and at the regional scale using satellite data simultaneously. This provides advantages in both coverage and response speed to potential fire events.

To illustrate the system workflow, the following diagram presents the integrated system structure:

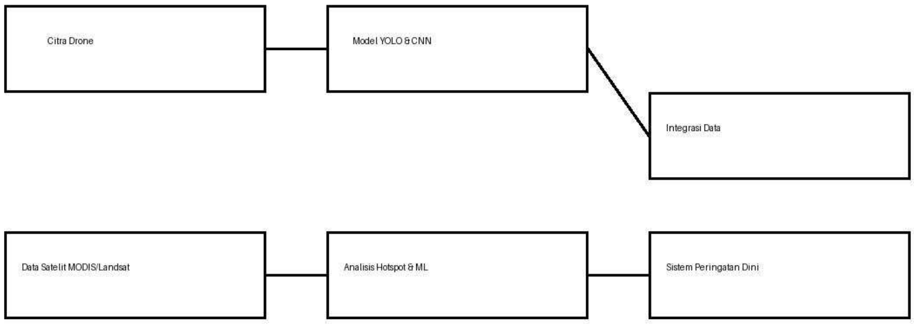

Figure 1. Fire Detection System Integration Diagram

The diagram shows that the system operates through two main pathways: visual detection and hotspot analysis. These two pathways are then integrated to produce a final decision in the early warning system. This approach enables cross-validation between visual detection results and satellite data, thereby reducing the likelihood of detection errors.

In addition, integration with probabilistic prediction models such as ProbFire provides added value to the early warning system. This model is capable of predicting fire potential based on climate factors and land conditions (Mezbahuddin & Victorin, 2022). By combining detection and prediction approaches, the developed system has a more comprehensive capability in supporting fire mitigation efforts.

The implications of this study indicate that the integrated use of computer vision and remote sensing technology can enhance the effectiveness of forest fire early warning systems. The system not only improves detection accuracy but also provides faster and wider information to support decision-making. Therefore, this approach has strong potential for implementation in forest fire monitoring systems in Indonesia, particularly in high-risk regions such as Sumatra.

CONCLUSION

This study develops an early warning system for forest and land fires in Sumatra through the integration of computer vision and remote sensing data. The results show that YOLO- and CNN-based approaches are effective in detecting fire and smoke in real time with high accuracy, consistent with the findings of Usman and Suwarno (2024) and Muntarti et al. (2025). On the other hand, the use of satellite data such as MODIS and Landsat expands the monitoring coverage and supports regional hotspot identification (Indradjad et al., 2019). The integration of both approaches produces a more comprehensive system compared to single-method approaches, particularly in terms of accuracy, coverage, and response time.

In addition, the application of the multi-source data fusion concept has been proven to improve system reliability under various environmental conditions (Reis da Silva, 2023; Khalifeh et al., 2024). The developed system also shows advantages over IoT-based sensor approaches, which are limited to local coverage (Setiawan & Yanto, 2018), and can be further enhanced with probabilistic prediction models to support more proactive fire mitigation strategies (Mezbahuddin & Victorin, 2022).

Overall, this research contributes to the development of an intelligent, adaptive, and integrated early warning system. For future research, it is recommended to develop a real-time system connected to cloud-based platforms to improve scalability and enable broader national-level implementation.

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