AI-Based Forest Fire & Smoke Detection Using Aerial Imagery

1. Introduction

Forest fires are one of the most destructive natural disasters, causing severe damage to ecosystems, wildlife, human life, and property. Early detection of forest fire and smoke plays a crucial role in minimizing damage and enabling faster disaster response. With the advancement of Artificial Intelligence (AI) and Machine Learning (ML), automated detection systems using aerial imagery have become a promising solution for real-time monitoring.

This project focuses on designing an AI-based system to detect forest fire and smoke regions using feature-level analysis extracted from aerial imagery tiles. The system aims to support drone-based disaster monitoring and assist emergency response teams by identifying high-risk zones efficiently.

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2. Objectives

The primary objectives of this capstone project are:

- To understand the visual and spectral indicators of forest fire and smoke in aerial imagery
- To apply supervised machine learning techniques for fire and smoke detection
- To evaluate model performance using standard metrics such as precision, recall, F1-score, confusion matrix, and ROC-AUC
- To perform spatial risk analysis and visualize fire-prone regions using heatmaps
- To interpret AI predictions for effective drone deployment and disaster response

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3. Dataset Description

The dataset provided consists of tile-level features extracted from aerial imagery. Each row in the dataset represents a spatial tile and contains spectral, intensity, and texture-based features relevant to identifying fire or smoke presence. The target label indicates whether the tile contains fire/smoke or not.

Key Features and Their Relevance

- **Mean Red, Green, Blue Values**: Fire regions usually show higher red intensity, while smoke reflects more blue light.
- **Red-Blue Ratio**: Helps differentiate between fire flames and smoke clouds.
- **Intensity Standard Deviation**: Fire zones have higher intensity variations due to flames.
- **Edge Density**: Smoke tends to blur edges, while fire creates sharp contrasts.
- **Smoke Whiteness & Haze Index**: Useful for detecting smoke and atmospheric haze.
- **Hot Pixel Fraction**: Identifies localized hotspots indicating fire presence.

- **Local Contrast**: Higher in active fire regions.

The target variable **fire_label** is binary, where: - 0 indicates no fire or smoke - 1 indicates presence of fire or smoke

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4. Methodology

4.1 Data Preprocessing

- The dataset was loaded and explored to understand feature distributions.
- Features and labels were separated.
- Data was split into training and testing sets using a 75:25 ratio.
- Feature scaling was applied using StandardScaler to normalize input features.

4.2 Machine Learning Model

A **Random Forest Classifier** was chosen due to its robustness, ability to handle non-linear relationships, and strong performance on structured tabular data. The model was trained using multiple decision trees and ensemble learning techniques.

4.3 Model Evaluation

The trained model was evaluated using:

- **Precision**: Measures correctness of positive predictions
- **Recall**: Measures the model’s ability to detect actual fire/smoke regions
- **F1-Score**: Harmonic mean of precision and recall
- **Confusion Matrix**: Shows classification performance
- **ROC-AUC Curve**: Measures the model’s discriminative ability

The evaluation results demonstrated strong predictive performance, indicating the model’s effectiveness in detecting forest fire and smoke regions.

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5. Spatial Risk Analysis & Visualization

Since explicit geographical coordinates were not provided, spatial tile indices were used as proxies for spatial representation. The model generated a fire risk probability score for each tile.

A heatmap visualization was created using these risk scores, highlighting regions with higher likelihood of fire or smoke presence. Tiles with higher intensity on the heatmap represent higher fire risk zones, enabling quick identification of critical areas.

This spatial aggregation supports effective monitoring and prioritization in large forest regions.

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6. Drone-Based Disaster Response Interpretation

Based on the predicted fire risk scores, the following drone deployment strategies are recommended:

- Prioritize drone surveillance in regions with high predicted fire risk scores
- Use thermal and infrared sensors in areas with high hot pixel fractions
- Increase monitoring frequency in smoke-dominant regions
- Enable real-time alerts to emergency response teams
- Utilize drones for early-stage fire detection before large-scale spread

These strategies help improve response time, reduce damage, and enhance disaster management efficiency.

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7. Results and Discussion

The Random Forest model successfully identified fire and smoke regions with high accuracy and reliability. Feature importance analysis revealed that spectral ratios, hot pixel fraction, and haze-related features contributed most to prediction accuracy.

The spatial risk heatmap provided a clear visualization of fire-prone areas, making it easier for authorities to interpret and act upon the results.

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8. Limitations and Future Improvements

Limitations

- Absence of real geographical coordinates
- Dataset limited to feature-level information rather than raw imagery
- Binary classification without separating fire and smoke

Future Improvements

- Incorporate GPS coordinates for accurate spatial mapping
- Use Convolutional Neural Networks (CNNs) on raw aerial images
- Implement real-time drone video analysis
- Extend to multi-class classification (fire, smoke, normal)

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9. Conclusion

This project successfully demonstrates the application of AI and machine learning for forest fire and smoke detection using aerial imagery features. The developed system effectively identifies high-risk regions and provides actionable insights for drone-based disaster monitoring. With further enhancements and real-time integration, this approach can significantly contribute to early warning systems and environmental protection efforts.

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10. References

- Scikit-learn Documentation
- Research papers on AI-based fire detection
- Drone-based disaster monitoring studies