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Deep Learning-Based Multistage Fire Detection System and Emerging Direction

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Abstract: Fires constitute a significant risk to public safety and property, making early and accurate detection essential for an effective response and damage mitigation. Traditional fire detection methods have limitations in terms of accuracy and adaptability, particularly in complex environments in which various fire stages (such as smoke and active flames) need to be distinguished. This study addresses the critical need for a comprehensive fire detection system capable of multistage classification, differentiating between non-fire, smoke, apartment fires, and forest fires. We propose a deep learning-based model using a customized DenseNet201 architecture that integrates various preprocessing steps and explainable AI techniques, such as Grad-CAM++ and SmoothGrad, to enhance transparency and interpretability. Our model was trained and tested on a diverse, multisource dataset, achieving an accuracy of 97%, along with high precision and recall. The comparative results demonstrate the superiority of the proposed model over other baseline models for handling multistage fire detection. This research provides a significant advancement toward more reliable, interpretable, and effective fire detection systems capable of adapting to different environments and fire types, opening new possibilities for environmentally friendly fire type detection, ultimately enhancing public safety and enabling faster, targeted emergency responses.

Keywords: fire detection; deep learning; computer vision; convolutional neural network; explainable AI

Citation: Sultan, T.; Chowdhury, M.S.; Safran, M.; Mridha, M.F.; Dey, N. Deep Learning-Based Multistage Fire Detection System and Emerging Direction. *Fire* **2024**, *7*, 451. https://doi.org/10.3390/fire7120451

Academic Editor: Lizhong Yang

Received: 20 September 2024
Revised: 23 November 2024
Accepted: 25 November 2024
Published: 30 November 2024

1. Introduction

Fire incidents are sudden, often catastrophic events that can occur in diverse environments, each presenting unique challenges in detection, containment, and response. These incidents involve rapid combustion of materials, resulting in intense heat, smoke, and toxic gases that spread through the air and surfaces, posing immediate and severe risks to human safety, property, and ecosystems [1,2]. The effects of fire are far-reaching; beyond threats to life; they cause extensive damage to property, destruction of infrastructure, environmental degradation, and long-term economic repercussions [3]. Fire scenarios can vary greatly depending on the environment: urban settings face risks from residential or commercial building fires, often triggered by electrical malfunctions, kitchen mishaps, or