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Research Proposal

on

AI-Driven Real-Time Fire Detection

and

3D Localization for Warehouse Safety

Scholar Name

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Introduction:

Bangladesh has had a tragic history of fire disasters in factories, warehouses, and shopping malls, claiming hundreds of lives yearly [1][2][3]. Fire incidents in industrial and warehouse settings pose severe risks to life and property, often resulting in catastrophic financial losses, casualties, and long-term economic setbacks. Traditional fire detection methods, such as smoke and temperature sensors, often fail due to limited range, delayed response times, and high false alarm rates [4], necessitating a more efficient, AI-driven approach for early fire detection and prevention. To minimize fire damage, it is crucial to detect fires early [5] and accurately locate their source. This study integrates the best-performing algorithm, the most efficient tiny-ML processor established sensor arrays and precise fire center coordinates.

Research Question:

This research seeks to investigate how deep learning models can enhance fire detection accuracy, reduce false alarms, and improve real-time performance in complex indoor settings. Specifically, it aims to analyze and compare different fire detection algorithms, evaluate their adaptability to warehouse environments. Additionally, it will assess the feasibility of integrating 3D localization with fire detection systems to improve situational awareness and emergency response. The key research questions addressed in this study include:

1. How well can deep learning-based fire detection models be optimized to improve accuracy while reducing false positive in warehouse environments?
2. Evaluate the state-of-the-art real-time fire detection, particularly in warehouse settings with occlusions and complex layouts?
3. How can 3D localization be effectively integrated with fire detection systems to enhance emergency response and fire tracking?

By addressing these questions, this research aims to develop a robust, efficient, and scalable AI-driven fire detection system that minimizes response time, enhances fire localization, and prevents loss of life and property in high-risk industrial settings.

Literature Review:

Recent research on fire detection systems emphasizes the need for deep learning models that are adaptable to diverse environments, particularly for real-time image-based fire detection. Such systems aim to improve detection accuracy, response time, and computational efficiency. Several deep learning (DL) models have been developed to enhance fire detection. Titu et al. [6] proposed a lightweight distillation-based technique for real-time accuracy improvement, while Cao et al. [7] introduced an enhanced YOLOv5s model, surpassing YOLOv5/6/7 and Fire-YOLO with an mAP of 61.5% on an online fire dataset. Li et al. [8] developed YOLOGX, incorporating GD mechanisms, SE_ResNetXt, and Focal-SioU loss, achieving an mAP@0.5 of 80.92% using the D-Fire dataset, particularly excelling in detecting small fires. Hossain et al. [9] proposed a 3D coordinate detection algorithm using two cameras with YOLOv3, integrating horizontal and vertical projection formulas. For 2D location detection, Hong et al. [10] introduced a computer graphics transformation matrix. A modular approach allows dynamic activation of video analysis modules based on environmental complexity [11], reducing computational load while ensuring adaptability. By integrating these advanced techniques, fire detection systems can optimize performance across diverse settings, from low-activity indoor environments to high-activity industrial applications, ensuring efficiency, accuracy, and scalability.

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Table 1: Performance Comparison of Applied Deep Learning Methods for Fire Detection

Applied DL Method	**Accuracy**	**mAP**	**Fire Center Localization**	**Environment**
CNN-based fire Detection [12]	94.50%	0.91	NO	Outdoor
YOLOGX algorithm [8]	80.92%	--	NO	Outdoor
UAV-Based Fire Detection [13]	80.80%	0.64	NO	Outdoor
CNN with Surveillance Camera [14]	94.93%	0.86	NO	Outdoor
Feature Fusion [7]	61.50%	0.61	NO	Outdoor
Shallow Guide Deep Network (SGDNet) [15]	85.40%		NO	Indoor
Vision-based flame detection [10][16]	98.00%		Yes	Indoor

Table 2 : Comparison of Fire Detection Methods Based on Delay, Accuracy, and Complexity

Fire Detection Method	**Delay**	**Accuracy**	**Complexity**
Chemical Gas Sensor [15]	Low	High	Moderate
Optical Techniques [15]	Moderate	Moderate	High
Deep Learning Image Detection [16]	Low	High	High
Traditional Smoke Detectors[16]	High	Moderate	Low
Water Mist System [16]	Moderate	High	Moderate

Knowns and Unknowns:

1. **Advantages of Video-Based Detection:** Video-based fire detection systems offer significant advantages over traditional methods, such as smoke and temperature sensors, in crucial environments traditional sensors may fail due to their limited range and slow response times [17] [16] , additionally, power consumption plays a crucial role in their efficiency [6].

2. **Fire detection DL ML Model:** The YOLO computer vision model is widely used for fire detection; however, despite its high capabilities, challenges such as accuracy limitations and false positives highlight the need for more robust improvements [17].

3. **Real-Time Processing Limitations:** The balance between accuracy and processing speed continues to be a key challenge. Early methods resized images to reduce computational load, which can affect detection accuracy [10].

Research Gaps:

2. **Algorithm Limitations:** Existing datasets lack human interactions, which may result in reduced performance. Lacks specific adaptations for warehouse scenarios where occlusions and complex layouts can hinder YOLO's performance [8]. Existing real-time feature reduction methods are leading to high false alarms.

3. **Data Scarcity :** The current datasets often do not include varied scenarios consisting of plenty of objects, typical in warehouses, such as different storage configurations and fire behaviors [13] [15] [18].

4. **Locating Coordinate:** Current video surveillance systems are not yet well-developed for 3D location detection [9][12], and the integration of fire detection with location tracking remains an unresolved challenge.

5. **Optimized Alert System Integrity:** Current systems primarily utilize single-channel communication methods [16]. The need for improved detection models, yet the communication of alerts to non-expert users is often overlooked [17].

This research aims to address the gap in studying both algorithms and hardware for detecting natural fire sources. It will focus on adapting fire detection systems for indoor environments, particularly warehouses, by comparing different controllers and identifying optimal components.

Methodology:

Step -1 : System Design & Architecture

- Develop a multi-sensor fire detection framework combining visual data and environmental data (smoke, temperature, and gas sensors). \
- Employ an edge-computing device (Jetson Orin Nano) for real-time processing. Use sensor fusion to integrate multiple inputs and enhance accuracy.

Step – 2 : Simulation & Modeling

- Implement and train deep learning models using PyTorch.
- Conduct simulations with synthetic and benchmark datasets to validate detection accuracy, false alarm rates, and latency.

Step -3 : **Prototype Development**

- Assemble core components (cameras, sensors, networking, alert system).
- Test functionality in controlled lab conditions with fire, smoke, and gas scenarios.

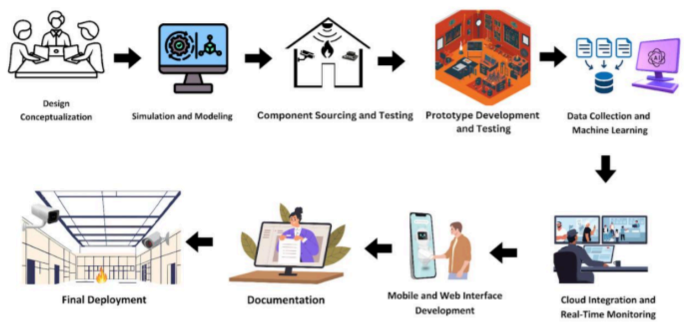

Fig: Pictorial representation of the methodology of the early fire detection system development process and documentation.

Step -4 : **Data Collection & Training**

- Collect multimodal data under different warehouse fire conditions.
- Preprocess and extract key features.Train models (based on step 2) for detection, classification, and hazard-level prediction.

Step - 5: Evaluation **& Validation**

- Measure performance against traditional fire detection systems using metrics: accuracy, precision, recall, false positives, and response time.

Expected Outcomes:

1. **Optimized Deep Learning Fire Detection (RQ1)**
   - Development of a deep learning-based fire detection system that significantly reduces false positives while improving detection accuracy in warehouse environments.
2. **Enhanced Real-Time Detection in Complex Warehouses (RQ2)**
   - Clear benchmarking results showing improved response times and reliability compared to existing commercial fire detection systems.
3. **Integration of 3D Localization for Fire Tracking (RQ3)**
   - Validation that 3D fire localization reduces evacuation time and enhances targeted firefighting strategies.

Practicalities:

Expenditure	**Details**	**Per unit cost**	**Unit**	**Estimated Cost (BDT)**
Jetson Orin NX (16GB)	A high-performance computing module essential for AI-based edge computing and processing. This will be used as the core processing unit for the system.	153,770.00	1	153,770.00
IR camera	Infrared cameras are required for night vision and thermal imaging capabilities, enabling effective monitoring in low-light environments.	49,000.00	2	98,000.00
IP camera	These cameras will provide high-resolution surveillance footage for real-time monitoring.	3500	4	14,000.00
Sensors (Smoke, Humidity, CO2)	Multiple environmental sensors will be deployed to monitor crucial atmospheric conditions such as smoke, humidity, and carbon dioxide levels.	15000	4	60,000.00
Storage & Power	Storage devices and power management solutions are required to ensure uninterrupted data recording and system functionality.	16000	1	16,000.00
Networking	Essential networking equipment will be used to establish stable communication between system components.	8000	1	8,000.00
Alert System	A dedicated alert system for real-time notifications and alarms in case of anomalies.	10000	1	10,000.00

Software & Cloud (Initial Setup)	This covers the cost of setting up cloud-based infrastructure, software licenses, and initial development expenses.	5000	1	5,000.00
Field Test cost	Expenses related to testing the system in real-world environments, including logistics and deployment costs.	10000	1	10,000.00
	Total			374,770.00

Potential risks include model inaccuracies, hardware limitations, data scarcity, and operational issues like sensor failures or connectivity loss. These will be managed through proper data training, while integrating effective fire management strategies such as rapid alert systems with the help of fire service will be taken to ensure the fire destructions.

Conclusion:

This study presents an AI-driven fire detection system for warehouses, combining deep learning, multi-sensor fusion, and 3D localization. The approach improves detection accuracy, reduces false alarms, and enables real-time response in complex environments. By bridging algorithmic innovation with practical deployment, it enhances fire safety and minimizes loss of life and property.

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