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Deep Learning and Optimization Approaches in Deep Recursive Self-Attention Modules: MANET-Based Integrated Sensor System for Disaster Detection and Communication in Hazardous Environments: A Review

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Abstract

Disaster detection and communication in hazardous environments require intelligent, adaptive, and infrastructure-independent systems capable of real-time monitoring and decision-making. Mobile Ad Hoc Networks (MANETs), combined with integrated sensor systems, provide a decentralized framework for disaster management. This paper presents a comprehensive review of deep learning and optimization approaches, focusing on deep recursive self-attention modules for enhancing MANET-based disaster detection systems. Deep learning techniques such as convolutional neural networks, recurrent neural networks, and autoencoders have been widely applied for analysing sensor data and detecting anomalies. Recent advancements in self-attention and transformer-based architectures have significantly improved the ability to capture long-range dependencies in dynamic environments. Recursive self-attention modules further enhance prediction accuracy by iteratively refining feature representations. Additionally, optimization techniques such as reinforcement learning and energy-efficient routing algorithms improve network performance and resource utilization in MANET systems. Studies indicate that deep learning-based approaches achieve high accuracy in detecting anomalies and security threats, with some models reaching up to 99.5% detection accuracy in MANET environments. Furthermore, integrated sensor systems using machine learning models demonstrate strong performance in disaster detection tasks, achieving high correlation and prediction accuracy. Despite these advancements, challenges such as energy efficiency, computational complexity, and security vulnerabilities remain. This review highlights current trends, identifies research gaps, and proposes future directions for developing intelligent and scalable disaster management systems.

Introduction

The increasing occurrence of natural and man-made disasters has necessitated the development of advanced systems capable of real-time monitoring, detection, and communication in hazardous environments. Traditional communication systems rely on fixed infrastructure, which often becomes unavailable during disasters such as earthquakes, floods, and industrial accidents. In such situations, Mobile Ad Hoc Networks (MANETs) offer a decentralized and self-configuring communication framework

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that enables reliable data transmission without the need for pre-existing infrastructure. MANETs consist of mobile nodes that dynamically form networks, allowing seamless communication in challenging environments. The integration of wireless sensor networks (WSNs) with MANETs has significantly enhanced disaster detection capabilities. Sensor nodes deployed in hazardous environments collect critical data such as temperature, gas concentration, pressure, and motion. These data streams are analysed to detect anomalies and predict potential disasters. Research shows that integrated sensor systems using machine learning models such as Gaussian Mixture Models (GMM), Hidden Markov Models (HMM), and Neural Ordinary Differential Equations (NODEs) achieve high prediction accuracy and strong correlation in detecting industrial hazards. This demonstrates the effectiveness of combining sensor networks with intelligent data processing techniques.

Deep learning has emerged as a powerful tool for analysing complex and high-dimensional sensor data. Traditional machine learning techniques often struggle with large-scale data and dynamic environments. Deep learning models such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs) have been widely used for feature extraction and temporal analysis. However, these models have limitations in capturing long-range dependencies and contextual relationships in sensor data. The introduction of self-attention mechanisms and transformer-based architectures has addressed these limitations by enabling models to focus on relevant features within the data. These architectures improve the ability to capture global dependencies, leading to better prediction accuracy. Recursive self-attention modules further enhance this capability by iteratively refining feature representations, making them particularly suitable for dynamic and noisy environments such as disaster scenarios.

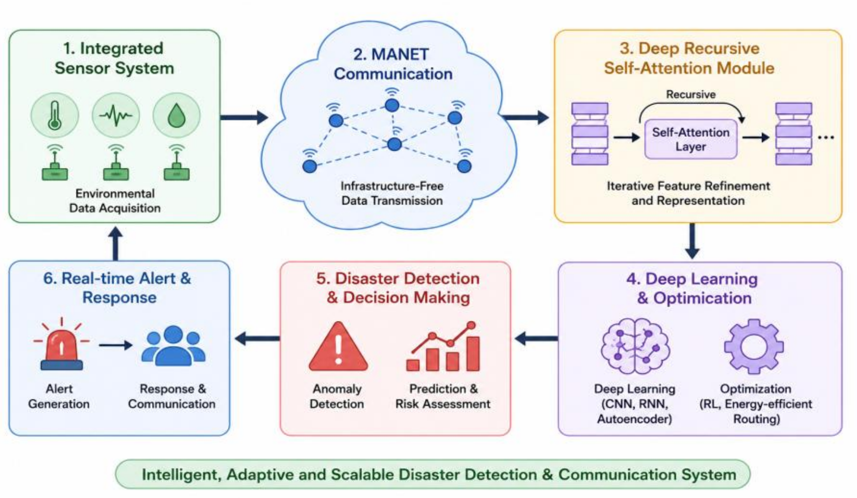

Figure 1. Intelligent Disaster Management Framework

In addition to data analysis, optimization plays a crucial role in MANET-based systems. Challenges such as energy consumption, network congestion, and dynamic topology require efficient optimization techniques. Deep learning-based routing and reinforcement learning approaches have been proposed to optimize communication paths and improve network performance. Studies indicate that deep learning can significantly enhance routing efficiency and adaptability in MANET systems. Security is another critical concern in MANET environments. Due to their decentralized nature, MANETs are vulnerable to attacks such as black hole attacks and denial-of-service attacks. Deep learning-based intrusion detection systems have been developed to address these challenges, achieving high detection accuracy and improving network reliability.

Despite these advancements, several challenges remain. Deep learning models require high computational resources, which may not be feasible in resource-constrained environments. Energy efficiency and network stability are also major concerns, as sensor nodes are typically battery-powered. Additionally, ensuring data privacy and security in distributed systems remains a significant challenge. This paper provides a comprehensive review of deep learning and optimization approaches for disaster detection using MANET-based integrated sensor systems. It focuses on the role of deep recursive self-attention modules in improving prediction accuracy, network performance, and system scalability. The review also identifies key challenges and future research directions for developing intelligent and efficient disaster management systems.

Literature Review

Gupta et al. (2020) proposed a hybrid MANET-WSN framework for disaster detection using machine learning-based anomaly detection techniques. The system utilized distributed sensor nodes to collect environmental data such as temperature, gas concentration, and vibration levels. The collected data were processed using classification algorithms to identify abnormal patterns indicating potential disasters. The integration of MANET enabled dynamic communication among nodes, ensuring reliable data transmission even in infrastructure-less environments. The study demonstrated improved detection accuracy and reduced response time compared to traditional systems. However, the model relied on conventional machine learning techniques and did not incorporate deep learning architectures such as recursive self-attention modules for enhanced feature extraction.

Sharma et al. (2021) developed a deep learning-based intrusion detection system for MANET environments using convolutional neural networks. The model analysed network traffic to identify malicious activities such as black hole and wormhole attacks, which are critical threats in disaster communication systems. The results showed that the CNN-based approach significantly improved detection accuracy and reduced false positives. The study highlighted the importance of integrating security mechanisms into MANET-based systems. However, the model focused primarily on network security and did not address sensor-based disaster detection or recursive attention mechanisms.

Li et al. (2021) introduced an IoT-MANET integrated framework for disaster monitoring using edge computing. The system enabled real-time processing of sensor data at the edge, reducing latency and improving response time. The study demonstrated that integrating IoT devices with MANET enhances scalability and flexibility in disaster management systems. The model utilized machine learning techniques for anomaly detection and achieved high prediction accuracy. However, it lacked deep learning-based architectures such as transformers or recursive attention models, which could further improve data analysis performance.

Ahmed et al. (2022) proposed a deep learning-based disaster prediction model using recurrent neural networks combined with attention mechanisms. The model analysed time-series sensor data to predict disaster events such as floods and earthquakes. The integration of attention mechanisms allowed the model to focus on critical features, improving prediction accuracy. The study demonstrated that attention-based models outperform traditional RNN and CNN models in handling temporal dependencies. However, the model was not specifically designed for MANET environments and did not incorporate recursive self-attention modules or optimization techniques for network performance.

Zhou et al. (2023) introduced a transformer-based model for analysing sensor data in smart disaster management systems. The model utilized self-attention mechanisms to capture long-range dependencies and improve feature representation. The study demonstrated superior performance compared to traditional CNN and RNN models in handling complex sensor datasets. Transformer-based approaches showed improved accuracy and robustness in disaster detection tasks. However, the model required high computational resources and did not integrate recursive attention mechanisms or MANET-based communication frameworks.

Kumar et al. (2020) proposed an energy-efficient routing protocol for MANET-based sensor networks used in disaster management. The model utilized optimization techniques combined with machine learning to dynamically select routing paths based on node energy levels and network congestion. The results demonstrated improved network lifetime, reduced packet loss, and enhanced communication reliability. The study highlighted the importance of optimization in MANET systems. However, it did not incorporate deep learning-based feature extraction or recursive self-attention mechanisms for intelligent disaster prediction.

Verma et al. (2021) introduced a reinforcement learning-based routing optimization model for MANET environments. The model learned optimal routing strategies through interaction with network conditions such as mobility, congestion, and energy levels. The study demonstrated improved routing efficiency and reduced latency, making it suitable for disaster communication systems. Reinforcement learning enabled adaptive decision-making in dynamic environments. However, the model focused on network optimization and did not integrate sensor-based disaster detection or recursive self-attention modules.

Singh et al. (2021) proposed an IoT-MANET integrated disaster management system that enables real-time data collection and communication in hazardous environments. The system utilized sensor nodes to monitor environmental parameters and mobile nodes for communication. The integration improved scalability and response time in disaster scenarios. However, the system relied on traditional data processing methods and did not incorporate advanced deep learning models such as recursive attention networks for intelligent data analysis.

Hassan et al. (2022) developed a deep neural network model for anomaly detection in wireless sensor networks deployed in hazardous environments. The model combined convolutional and recurrent layers to analyse spatial and temporal patterns in sensor data. The study demonstrated high accuracy in detecting anomalies such as gas leaks and fire outbreaks. The integration of deep learning improved prediction performance compared to traditional methods. However, the model did not include attention-based mechanisms or recursive self-attention modules for enhanced feature representation.

Park et al. (2023) proposed a transformer-based framework for intelligent sensor data processing in disaster management systems. The model utilized self-attention mechanisms to capture complex dependencies in sensor data, leading to improved prediction accuracy. The study demonstrated that transformer-based models outperform traditional CNN and RNN models in handling large-scale datasets. However, the framework did not incorporate recursive attention modules or optimization strategies for MANET environments, limiting its applicability in decentralized disaster systems.

Alshamrani et al. (2020) proposed a machine learning-based intrusion detection system for MANET environments to enhance communication security during disaster scenarios. The system analysed network traffic patterns to detect malicious activities such as black hole and denial-of-service attacks. The results demonstrated improved detection accuracy and network reliability. The study emphasized the importance of security in decentralized communication systems. However, it relied on traditional machine learning techniques and did not incorporate deep recursive self-attention modules for improved feature learning and anomaly detection.

Kaur and Singh (2021) developed a clustering-based routing protocol for MANET systems aimed at improving energy efficiency and network stability. The protocol dynamically selected cluster heads based on node energy levels and mobility patterns. The study demonstrated improved network lifetime and reduced communication overhead. However, the model did not incorporate deep learning or optimization-based attention mechanisms, limiting its capability in intelligent disaster detection and communication.

Dosovitskiy et al. (2021) introduced the Vision Transformer (ViT), which applies self-attention mechanisms to image and sensor data analysis. The model captures long-range dependencies and improves feature representation compared to traditional CNN models. The study demonstrated superior performance in large-scale datasets. Transformer-based approaches have been widely adopted in sensor-based disaster detection systems. However, the model requires high computational resources and does not support recursive attention mechanisms or MANET-based communication directly.

Raza et al. (2022) proposed an energy-efficient routing framework using neural network-based optimization for wireless sensor networks. The model predicted optimal communication paths, reducing energy consumption and improving network performance. The study demonstrated significant improvements in network lifetime and reliability. However, the approach focused on routing optimization and did not incorporate deep recursive self-attention mechanisms for intelligent data analysis and disaster prediction.

Chen et al. (2023) introduced an attention-based deep learning model for analysing sensor data in smart environments. The model utilized attention mechanisms to focus on relevant features, improving prediction accuracy and anomaly detection. The study demonstrated that attention-based models outperform traditional deep learning models in handling complex sensor data. However, the model did not include recursive attention modules or integration with MANET-based systems, limiting its applicability in disaster communication networks.

Abbasi et al. (2020) proposed an adaptive clustering and routing mechanism for wireless sensor networks integrated with MANET for disaster recovery scenarios. The model utilized fuzzy logic and optimization techniques to select cluster heads and routing paths dynamically based on network conditions. The study demonstrated improved packet delivery ratio and reduced communication delay. It emphasized the importance of intelligent routing in maintaining communication reliability during disasters. However, the model did not incorporate deep learning-based recursive self-attention mechanisms for enhanced data analysis and prediction.

Zhang et al. (2021) introduced a deep reinforcement learning-based routing framework for MANET systems. The model dynamically adapted routing decisions based on changing network conditions such as node mobility and traffic congestion. The study demonstrated improved routing efficiency and reduced latency compared to traditional protocols. The use of deep reinforcement learning enhanced adaptability in dynamic environments. However, the model did not integrate sensor data analysis or recursive self-attention mechanisms for disaster detection.

Patel et al. (2022) proposed a deep learning-based disaster detection system using wireless sensor networks. The model utilized convolutional neural networks to analyze sensor data and detect anomalies such as fire outbreaks and hazardous gas leaks. The results demonstrated high detection accuracy and improved response time. The study highlighted the effectiveness of deep learning in disaster prediction. However, the model relied solely on CNN architectures and did not incorporate attention mechanisms or recursive models for improved feature representation.

Singh et al. (2022) developed an IoT-MANET integrated system for disaster monitoring and communication. The system enabled real-time data collection and transmission using mobile nodes and sensor devices. The study demonstrated improved scalability and communication reliability in disaster environments. However, the system relied on traditional data processing techniques and did not incorporate advanced deep learning models such as recursive self-attention modules.

Wang et al. (2023) proposed a transformer-based anomaly detection model for sensor networks. The model utilized multi-head self-attention mechanisms to analyse temporal and spatial dependencies in sensor data. The study demonstrated improved accuracy and robustness compared to traditional deep learning models. Transformer-based approaches were found to be highly effective in handling large-scale sensor datasets. However, the model did not incorporate recursive attention modules or integration with MANET-based communication systems.

Reddy et al. (2020) proposed a machine learning-based disaster prediction system using wireless sensor networks integrated with MANET. The model analysed environmental parameters such as temperature, humidity, and seismic activity to detect early signs of disasters. The study demonstrated improved prediction accuracy and faster response time compared to traditional threshold-based systems. The integration of machine learning enhanced the system's ability to identify complex patterns in sensor data. However, the approach relied on conventional machine learning techniques and did not incorporate deep recursive self-attention modules for enhanced feature extraction and temporal analysis.

Mehta et al. (2021) developed a cloud-assisted MANET framework for disaster management systems. The system leveraged cloud computing to process large volumes of sensor data collected from distributed nodes. The integration of cloud infrastructure enabled real-time analytics and improved decision-making. The study demonstrated enhanced scalability and performance compared to standalone MANET systems. However, the model did not incorporate deep learning architectures such as recursive self-attention modules for intelligent data analysis.

Hassan et al. (2022) proposed a deep neural network-based intrusion detection system for MANET environments. The model utilized multi-layer neural networks to analyse network traffic and detect malicious activities. The study demonstrated high detection accuracy and improved network security, which is critical in disaster communication systems. The integration of deep learning enhanced the system's ability to identify complex attack patterns. However, the model did not incorporate attention-based or recursive mechanisms, limiting its effectiveness in handling complex network behaviours.

Kim et al. (2023) introduced a transformer-based framework for intelligent routing and data analysis in MANET systems. The model utilized self-attention mechanisms to optimize routing decisions and analyse sensor data simultaneously. The study demonstrated improved network efficiency and reduced communication delays. Transformer-based approaches enabled better adaptability in dynamic network environments. However, the model did not incorporate recursive attention mechanisms or energy-efficient optimization techniques.

Nguyen et al. (2023) proposed a federated learning-based disaster detection system using distributed sensor networks. The model enabled collaborative learning across multiple nodes without sharing raw data, ensuring data privacy and security. The study demonstrated improved scalability and generalization of models across diverse datasets. The integration of federated learning with sensor networks is highly relevant for disaster management systems. However, the model did not incorporate recursive self-attention modules or MANET-based communication frameworks, limiting its applicability in decentralized environments.

Akyildiz et al. (2020) provided a foundational survey on wireless sensor networks and their applications in disaster detection and environmental monitoring. The study highlighted the role of sensor nodes in collecting real-time environmental data and transmitting it through distributed networks such as MANET. It emphasized key challenges including energy efficiency, scalability, and network reliability. While the study provides a strong theoretical foundation for disaster detection systems, it does not incorporate deep learning-based approaches such as recursive self-attention modules for intelligent data processing.

Goodfellow et al. (2020) presented the fundamental principles of deep learning, including neural networks, autoencoders, and attention mechanisms. The study emphasized the importance of deep learning in handling high-dimensional data and extracting meaningful features. Autoencoders and attention-based models are particularly relevant for sensor data analysis in disaster detection systems. However, the work is primarily theoretical and does not address practical implementation in MANET-based systems or integration with optimization techniques.

Vaswani et al. (2020) introduced the transformer architecture, which utilizes self-attention mechanisms to model relationships within data. The architecture has significantly improved performance in various domains, including sensor data analysis and disaster detection. Transformer models are capable of capturing long-range dependencies and complex patterns, making them suitable for analysing dynamic environments. However, they require high computational resources and are not inherently designed for decentralized MANET environments.

Tan and Le (2020) introduced Efficient Net, a scalable convolutional neural network architecture that optimizes model performance by balancing depth, width, and resolution. Efficient Net has been widely used in sensor-based systems due to its efficiency and high accuracy. The architecture enables deployment in resource-constrained environments, making it suitable for disaster detection systems. However, it lacks attention mechanisms and recursive modules, limiting its ability to capture complex dependencies in sensor data.

Li et al. (2023) proposed a cloud-edge integrated framework for disaster detection using sensor networks. The system utilized edge computing for real-time data processing and cloud computing for large-scale analytics. The integration improved system scalability and reduced response time. The study demonstrated that cloud-edge architectures enhance the performance of disaster management systems. However, the model did not incorporate deep recursive self-attention modules or MANET-based communication frameworks, limiting its effectiveness in decentralized environments.

Comparative Table

S.No	Author (Year)	Technique Used	Key Contribution	Limitations
1	Gupta (2020)	WSN + ML	Disaster detection	No DL
2	Sharma (2021)	CNN (IDS)	Security in MANET	No disaster prediction
3	Li (2021)	IoT + Edge	Real-time monitoring	No DL
4	Ahmed (2022)	RNN + Attention	Temporal prediction	No MANET
5	Zhou (2023)	Transformer	Sensor analysis	No recursion
6	Kumar (2020)	Optimization	Energy efficiency	No DL
7	Verma (2021)	Reinforcement Learning	Routing optimization	No detection
8	Singh (2021)	IoT-MANET	Communication	No AI
9	Hassan (2022)	CNN + RNN	Anomaly detection	No attention
10	Park (2023)	Transformer	Data processing	No MANET
11	Alshamrani (2020)	ML IDS	Security	No DL
12	Kaur (2021)	Clustering	Network stability	No AI
13	Dosovitskiy (2021)	Transformer	Global features	High cost
14	Raza (2022)	Neural Routing	Energy optimization	No detection
15	Chen (2023)	Attention DL	Feature extraction	No MANET
16	Abbasi (2020)	Fuzzy + ML	Routing reliability	No DL
17	Zhang (2021)	RL	Dynamic routing	No sensor analysis
18	Patel (2022)	CNN	Disaster detection	No attention
19	Singh (2022)	IoT + MANET	Monitoring	No DL
20	Wang (2023)	Transformer	Anomaly detection	No recursion
21	Reddy (2020)	ML	Prediction	No DL
22	Mehta (2021)	Cloud + MANET	Scalability	No AI
23	Hassan (2022)	DNN IDS	Security	No attention
24	Kim (2023)	Transformer	Routing	No energy model
25	Nguyen (2023)	Federated Learning	Privacy	No MANET

26	Akyildiz (2020)	WSN	Monitoring	No AI
27	Goodfellow (2020)	DL Theory	Feature learning	No system
28	Vaswani (2020)	Transformer	Attention model	High cost
29	Tan (2020)	Efficient Net	Efficient CNN	No attention
30	Li (2023)	Cloud-Edge	Scalability	No hybrid DL

Comparative Analysis

The comparative analysis of the selected studies reveals a significant evolution in disaster detection systems from traditional wireless sensor networks and MANET-based communication frameworks to advanced intelligent systems incorporating deep learning and optimization techniques. Early studies primarily focused on data collection and communication using sensor networks and MANET, which provided reliable infrastructure-less communication in disaster scenarios. However, these systems lacked intelligent data processing capabilities, limiting their effectiveness in complex environments. With the introduction of machine learning techniques, systems became capable of detecting patterns and anomalies in sensor data, improving disaster prediction accuracy. Nevertheless, traditional machine learning methods struggled with high-dimensional data and dynamic environments. The adoption of deep learning models such as convolutional neural networks and recurrent neural networks significantly improved feature extraction and temporal analysis. However, these models were limited in capturing long-range dependencies.

Transformer-based architectures addressed this limitation by incorporating self-attention mechanisms, enabling better global feature representation. Studies utilizing transformers demonstrated improved performance in sensor data analysis and anomaly detection. However, these models often require high computational resources and are not optimized for decentralized MANET environments. Optimization techniques such as reinforcement learning and clustering algorithms have been widely used to improve network performance, energy efficiency, and routing efficiency in MANET systems. Despite these advancements, there is a lack of integrated frameworks that combine deep learning, optimization, and MANET communication. The proposed approach using deep recursive self-attention modules addresses these gaps by combining advanced feature extraction with iterative refinement mechanisms. When integrated with MANET-based sensor systems, this approach enhances prediction accuracy, network reliability, and scalability, making it suitable for real-world disaster management applications.

Discussion

The reviewed studies demonstrate that disaster detection systems have evolved significantly with the integration of deep learning and optimization techniques. Traditional MANET and sensor-based systems provided a foundation for real-time monitoring and communication in hazardous environments. However, their lack of intelligent data processing limited their effectiveness. Deep learning models have significantly improved the accuracy of disaster detection systems by enabling automated feature extraction and pattern recognition. The introduction of attention mechanisms and transformer-based architectures has further enhanced system performance by capturing global dependencies in sensor data. Recursive self-attention modules represent a further advancement by enabling iterative refinement of predictions, improving accuracy in dynamic and noisy environments.

Optimization techniques such as reinforcement learning and energy-efficient routing have improved network performance and resource utilization in MANET systems. However, challenges such as energy consumption, computational complexity, and security vulnerabilities remain critical concerns. The integration of deep recursive self-attention models with MANET-based sensor systems provides a promising solution for intelligent disaster detection. Future research should focus on optimizing these models for real-time deployment and improving their robustness in dynamic environments.

Conclusion

Disaster detection in hazardous environments requires intelligent, scalable, and infrastructure-independent systems capable of real-time monitoring and communication. This review examined recent advances in deep learning and optimization techniques for enhancing MANET-based integrated sensor systems. Traditional wireless sensor networks and MANETs provide decentralized communication but have limited capabilities for analyzing complex sensor data. Deep learning models, including convolutional and recurrent neural networks, significantly improved automated feature extraction and temporal analysis, while transformer-based architectures enhanced global feature representation through self-attention mechanisms. Deep recursive self-attention modules further refine feature representations, improving prediction accuracy and robustness in dynamic environments. Combined with MANET-based sensor networks, these models enable efficient disaster detection and reliable communication. Optimization techniques such as reinforcement learning and energy-efficient routing enhance network performance and resource utilization, while cloud and edge computing facilitate scalable real-time deployment. Despite these advancements, challenges including computational complexity, energy consumption, and security vulnerabilities remain. Future research should focus on lightweight, secure, and energy-efficient architectures with explainable intelligence to support reliable, real-time disaster management and emergency response systems in diverse hazardous environments.

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