

Research on Intelligent Early Warning and Prevention Control of Urban Building Fire Based on Multimodal Data Fusion

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ABSTRACT

Aiming at data fragmentation, delayed early warning and empirical-dependent emergency decision-making in current urban smart fire control, guided by national emergency planning policy, this paper constructs an intelligent early warning and emergency decision system with multimodal heterogeneous data fusion and deep learning. Sponsored by provincial undergraduate innovation project, Shandong Province is selected as research object. The research follows the route of field investigation, theoretical sorting, data collection, model construction, platform development and experimental verification. Five types of heterogeneous data are integrated, including historical fire records, sensor monitoring data, firefighting facility information, meteorological indicators and GIS spatial data. Relying on adaptive weighting algorithm, CNN-Transformer hybrid framework, Stacking ensemble learning and K-means-DFS combined algorithm, a three-layer fusion early warning model at data, feature and decision levels is established. On this basis, a six-layer cloud intelligent fire platform is developed, matching Shandong's actual situation with localized "Response-Execution-Safeguard" closed-loop emergency mechanism, meanwhile an all-day intelligent consultation module for public fire service is embedded. Practical experiments in multiple typical regions of Shandong verify that the overall early warning accuracy reaches 98%, and emergency resource scheduling time is controlled within 5 minutes to realize advanced regional fire risk prediction. The research results provide technical references for refined smart fire management of Shandong cities and supplementary practical cases for intelligent fire prevention research nationwide.

KEYWORDS

Multimodal data fusion; Smart fire protection; Fire risk early warning; Deep learning; Emergency decision-making; Shandong province

1 Introduction

1.1 Research Background

Rapid urban expansion and complicated urban functional layout make traditional passive fire management unable to satisfy modern fire prevention requirements. Modern cities mix high-rise commercial buildings, aging residential districts, industrial parks and scattered small stores. Complex building structures, dense electric pipelines and diversified fire usage bring numerous hidden fire dangers. Official statistics from 2015 to 2024 show China keeps high annual fire volume, with 908,000 fire accidents in 2024 alone, causing heavy casualties and massive economic losses. Fire statistics show electrical faults account for 37.8% of total fires, improper domestic fire use takes 31.9%, discarded cigarette butts lead to 13.8% of fire occurrences. Such hidden hazards feature high concealment and recurrence, difficult to be eliminated by regular manual inspection.

1.2 Research Objectives and Significance

The research targets to change traditional post-fire remedy mode. By breaking cross-departmental data barriers via multimodal fusion and deep learning, a layered early warning model and matched cloud platform are built, forming Shandong-oriented closed-loop emergency system to realize pre-warning dominated fire governance and replicable regional fire prevention scheme.

Theoretically, the study expands three-layer multimodal fusion into urban fire risk evaluation, improves the "data-early warning-emergency disposal" theoretical framework and enriches localized emergency management research of Shandong fire control. Practically, the system can discover hidden risks in advance to avoid large-scale fire disasters, shorten rescue preparation time and cut economic loss after popularized in Shandong cities, whose mature mode can be extended to other provinces of China.

1.3 Domestic and Overseas Research Status

Domestic intelligent fire research mainly focuses on 5G communication transformation, multi-sensor fire detecting hardware, three-layer IoT fire platform and AI fire prediction based on CNN and Transformer. However most existing studies focus on single community or park, lacking full-province empirical research with multi-source heterogeneous data in Shandong.

Foreign intelligent fire technology develops early in Europe and America, concentrating on spatial fire assessment, new sensing material development and GIS-based old town risk grading. But different urban planning, fire regulations and climate lead to poor adaptability of foreign algorithms in Shandong without secondary localization optimization.

Current research has verified multimodal fusion feasibility in fire early warning, but three obvious gaps exist: insufficient field verification for Shandong regional features; separation between early warning model and emergency scheduling system; lack of large-model-based public fire consulting service, which becomes the core research direction of this paper.

1.4 Research Content, Technical Route and Difficulties

Core research includes five parts: field questionnaire survey and theoretical collation in Shandong; multi-source data classification and standardized preprocessing; three-layer fusion early warning model and auxiliary risk identification submodel development; six-layer cloud platform construction and closed-loop emergency & consultation function realization; field pilot test and result optimization.

Technical route: literature review & field investigation → multi-source data collection and preprocessing → model building and parameter debugging → cloud platform modular development → regional pilot experiment → data analysis and system improvement.

Key difficulties cover unified timestamp alignment of heterogeneous data, parameter optimization of multi-algorithm combination and limited access to government confidential firefighting internal data.

1.5 Research Innovations

Theoretical innovation: apply three-layer multimodal fusion theory into urban fire early warning and perfect localized full-cycle emergency management system for Shandong fire governance.

Model innovation: combine adaptive weighting, CNN-Transformer and Stacking to realize joint analysis of spatial image and time-series data; K-means-DFS algorithm automatically locks high-risk concentration areas to fix single algorithm's defects.

Application innovation: embed large language model into grassroots fire platform, add 24-hour free public consultation besides professional early warning and scheduling functions to realize popular intelligent fire service.

2 Basic Theories and Core Technology Introduction

2.1 Urban Fire Risk Control Related Theory

According to hazard density, building fire resistance and firefighting resource layout, urban space is divided into extremely high, high, medium and low four risk grades. Dilapidated shantytowns and small chemical workshops belong to extremely high-risk area; large malls and industrial parks are high-risk zones; ordinary communities and roadside shops are medium-risk; suburban green space is low-risk region, providing threshold reference for model early warning setting.

Based on three combustion essentials, indoor decoration, chemical raw materials act as main combustibles; circuit breakdown and illegal hot work become key ignition sources; dry and windy weather accelerates fire spread, guiding the selection of meteorology, building and electrical monitoring indicators.

2.2 Multimodal Data Fusion & Deep Learning Principle

Multimodal fusion is divided into data, feature and decision three layers. Data layer uses adaptive weighting to denoise original sensor data; feature layer uses CNN for spatial feature extraction from pictures and Transformer for time-series rule mining, then splices two types of feature vectors; decision layer uses Stacking ensemble learning to integrate multiple prediction results with strong anti-error ability.

CNN extracts smoke and flame spatial features from monitoring videos; Transformer analyzes long-term changing rules of temperature, humidity and electric load data; Stacking uses multi-base model to output preliminary results and meta-regression model to synthesize final warning value.

"Response-Execution-Safeguard" closed-loop mechanism: Response refers to risk warning pushing after abnormal discovery; Execution means automatic intelligent rescue allocation after fire confirmation; Safeguard includes post-fire loss statistics and hidden danger rectification to form cyclic management. GIS-assisted distance matching algorithm realizes automatic nearby rescue resource assignment to replace traditional manual scheduling.

3 Fire Situation and Field Survey of Shandong Province

3.1 Regional Fire Distribution Characteristics of Shandong

Shandong has 16 prefecture-level cities with unbalanced fire risk distribution: southwest inland owns massive aging residential blocks and traditional factories; Jiaodong coastal areas gather high-rise buildings and large commercial complexes. Spring gale and summer high temperature accelerate fire occurrence. Spatially, fire risks cluster in old communities, suburban small processing plants and chemical parks, highlighting the demand of intelligent monitoring instead of manual patrol.

3.2 Questionnaire Investigation Result

Questionnaires are issued in Jinan, Qingdao, Tai'an, Binzhou and Heze targeting firemen, property managers, residents and enterprise safety staff. Survey shows traditional fire alarm equipment has high installation rate, while intelligent electrical monitoring system is poorly popularized. Common problems include aging equipment, high false-alarm rate, isolated data between different departments and expensive manual inspection cost. Most users expect more than 15 minutes in advance early warning and automatic fire location function. Three core industry bottlenecks are summarized: severe data island, post-fire-oriented early warning and low-efficiency artificial emergency scheduling.

3.3 Five Categories Data Sorting and Preprocessing

Five heterogeneous fire datasets include historical fire archives, real-time IoT sensor data, fire station & hydrant distribution data, daily meteorological parameters and GIS terrain-road information. Public data are obtained from official government open platform, while confidential data rely on offline cooperation with local pilot enterprises and communities.

Raw data are processed by abnormal value elimination, linear interpolation for short missing data and discard of long continuous missing samples. All indicators are normalized and unified by hourly timestamp to finish space-time matching. Cleaned data are split into training set, verification set and test set at 7:2:1 proportion, marked with four-level risk labels for model training iteration.

4 Three-Layer Multimodal Fusion Early Warning Model Construction

Data layer: adaptive weighting dynamically adjusts each sensor's weight according to historical error and real-time working state to reduce equipment-caused false alarm.

Feature layer: CNN-Transformer hybrid model extracts spatial-temporal dual features of fire risk from image and numerical monitoring data to complete cross-modal feature fusion.

Decision layer: Stacking takes LSTM, Random Forest and CNN as base learners, Logistic regression as meta-learner to synthesize multi-group prediction into final fire risk level, with weighted voting and Bayesian fusion as alternative schemes.

K-means-DFS auxiliary model clusters geographic units with similar hidden danger features to draw high-risk regional scope, searches abnormal mutation points from full amount time-series data, cooperates with visual flame identification to reduce missing alarm rate.

5 Six-Layer Intelligent Fire Cloud Platform Development

The cloud platform adopts six-layer framework: perception layer deploys various sensors and cameras for all-day data collection; transmission layer uses 5G and NB-IoT hybrid encrypted transmission; storage layer builds dedicated fire database based on MySQL and distributed cluster; processing layer uses Hadoop and Kafka to operate fusion algorithm; application layer contains 72h long-term risk prediction, risk thermal map, intelligent scheduling and escape route planning modules; user layer sets differentiated access permission for administrator, firefighter, enterprise and resident with multi-terminal access support.

Under closed-loop emergency mechanism, platform distinguishes equipment failure and real fire risk via multi-data cross-check; confirmed fire triggers automatic 119 linkage and rescue resource distribution; post-fire data are archived to guide regional hidden danger rectification and model upgrade.

After fine-tuned by Shandong local fire data, DeepSeek large model supports long-period risk prediction, dynamic scheduling optimization and post-fire rapid loss assessment. The multi-modal consultation module accepts text, voice and picture consultation, providing household fire prevention guidance, enterprise equipment maintenance suggestion

and regulatory inquiry service for grassroots supervisors.

6 Experimental Test and Result Analysis

Five typical pilot areas covering Jinan old communities, Qingdao industrial parks, Tai'an shopping malls, Binzhou roadside stores and Heze micro-enterprise clusters are selected, covering over 1200 monitored buildings. Test data show model comprehensive early warning accuracy reaches 98%, far higher than traditional single-sensor equipment; multi-source cross-check largely reduces false alarm; average rescue scheduling time shortens from over 30 minutes to less than 5 minutes, improving work efficiency by over 80%. The platform realizes 72-hour ultra-early regional risk prediction and automatic hotspot mapping, completing the shift from post-fire disposal to pre-risk prevention.

After pilot operation, most potential hidden dangers are solved at early stage and sporadic small fires drop obviously, cutting daily manual management cost. The research has finished software copyright registration of the platform, and the standardized construction plan can be promoted to all cities of Shandong Province.

7 Conclusion, Deficiency and Future Prospect

This paper constructs a complete intelligent early warning and emergency decision system based on multimodal data fusion, effectively solving data fragmentation, delayed warning and inefficient manual scheduling problems of Shandong urban fire governance. However limited by research fund, confidential data access restriction and construction cycle, pilot cannot cover all cities in Shandong and partial internal business data are unavailable to enrich training samples.

Future research will expand pilot scope continuously to supplement multi-scenario sample data and optimize model parameters; strengthen long-term data sharing cooperation with fire and emergency departments; develop lightweight platform version to lower deployment cost for county and township popularization. After further optimization, the whole set of intelligent fire prevention system can be promoted nationwide to boost urban fire safety intelligent upgrading.

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