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Research on Air-Ground Integrated Emergency Collaboration for Preventing Secondary Bridge Accidents

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Abstract: As critical nodes of transportation infrastructure, bridges play a vital role in ensuring structural safety and operational reliability, with their safety conditions directly impacting socio-economic development and public safety. However, current bridge monitoring and emergency management systems still face notable deficiencies in the timeliness of risk identification, the accuracy of early warnings, and the efficiency of emergency response. These shortcomings often lead to frequent secondary bridge accidents, resulting in severe casualties and economic losses. To address this issue, this paper proposes an air-ground integrated emergency warning system for bridges. By establishing a three-dimensional monitoring network comprising ground-based units, aerial-based units, vehicle-mounted mobile units, and a central data processing and warning center, the system enables comprehensive, all-weather, real-time monitoring of bridge structures. Leveraging multi-source data fusion technology, the system can accurately assess risk levels at the early stages of bridge damage. Additionally, machine learning and pattern recognition algorithms are employed to rapidly generate warning information. This innovative solution offers a new approach to bridge safety warning and emergency response, holding significant value for ensuring the stable operation of transportation networks.

Keywords: Bridge Safety; Secondary Accidents; Air-Ground Integration; Emergency Warning System.

1. Introduction

As critical hubs of modern transportation networks, bridge safety directly influences socio-economic stability and public safety[1]. In the context of rapidly increasing traffic volumes and frequent extreme events, bridge accidents increasingly exhibit chain-amplification effects[2]. Structural damage induced by initial accidents, combined with failures in emergency response mechanisms, can easily trigger secondary disasters[3]. Typical case studies demonstrate this severity: rescue delays following the collapse of South Korea's Seongsu Bridge[4] resulted in a secondary mortality rate of 31.25%. Similarly, in the 2024 ship collision at Guangzhou's Lixinsha Bridge, secondary vehicle impacts led to five fatalities, with total losses estimated at 5 to 8 times those of the initial incident[5]. The root cause lies in the inherent limitations of traditional manual inspections and localized monitoring systems[6], which suffer from delayed risk identification and fragmented multi-source data integration. These shortcomings render them inadequate for addressing the coupled effects of diverse risks, including structural failures (e.g., the resonant collapse of the Tacoma Narrows Bridge[7]), natural disasters (e.g., bridge damage during the Hanshin Earthquake[8]), and impact accidents (e.g., the I-35W Mississippi River bridge collapse in the United States[9]). To overcome these challenges, this research leverages air-ground integration technology to develop a real-time, dynamic sensing system. This system integrates satellite remote sensing, unmanned aerial vehicle (UAV) inspections, and ground-based sensor networks[10]. It specifically addresses critical issues such as the delayed detection of hidden defects and disruptions in emergency response processes. The ultimate goal is to establish a robust, all-weather risk early-warning and coordinated response mechanism, thereby providing an innovative solution for curbing the chain-reaction evolution of bridge accidents.

2. Components of the Air-Ground Integrated Emergency Warning System

The system comprises four integral components: the subgrade monitoring unit, the aerial monitoring unit (UAV), the vehicle-mounted reception unit, and the data processing and early warning center. These units operate in concert to ensure efficient bridge safety monitoring and emergency response.

(1) Subgrade Monitoring Unit

The subgrade monitoring unit incorporates an optimized configuration of high-definition cameras, infrared thermal imagers, laser scanners, and communication equipment. Leveraging 4G/5G and optical fiber hybrid networking technology, it establishes a highly reliable data transmission channel. Data encryption and redundant transmission mechanisms ensure real-time performance and information security. Through multi-dimensional data fusion (visible light images, thermal radiation maps, and 3D point clouds), this unit provides a comprehensive sensory foundation for subsequent structural state assessment and incident early warning. It effectively supports the early detection of hidden bridge defects and the disruption of accident chain evolution.

(2) Aerial Monitoring Unit

Traditional embroidery patterns often have strong freehand brushwork characteristics. For designers, they do not pursue the perfect proportion too much, but pay more attention to the meaning of the pattern itself and the emotional effect brought

by the pattern.



Fig 1. Basic Composition of Subgrade Monitoring Unit

Traditional embroidery patterns have a very strong freehand effect. In particular, part of the pattern only through some simple lines, to draw the content, can be very vivid expression of the original features. In the development of embroidery art, designers need to grasp the characteristic expression of freehand brushwork, recognize the inherent laws of things, and then show the profound connotation of embroidery art.

(3) Vehicle-mounted Command Center

The Vehicle-mounted Command Center, equipped with integrated communication and processing units, achieves persistent warning coverage through primary and backup data links. Real-time warnings regarding traffic incidents and structural anomalies are decoded and relayed to the driver via multi-modal human-machine interface and ADAS coordination. A bidirectional feedback channel is incorporated, closing the "Warning-Response-Verification" loop and substantially improving the vehicle's active safety performance under complex driving conditions.

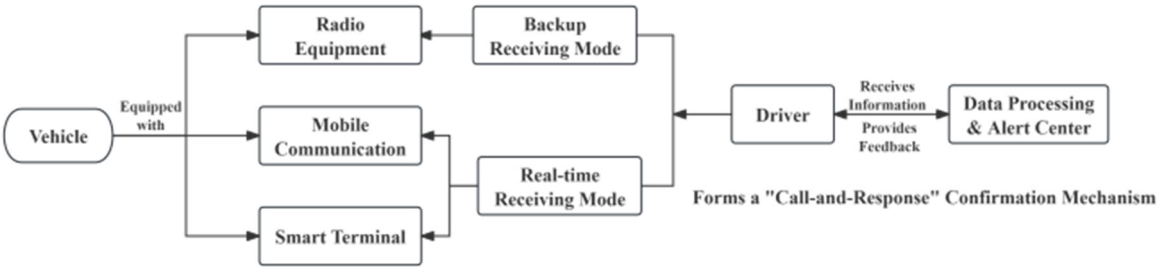


Fig 2. Basic Composition of Vehicle-based Monitoring Unit

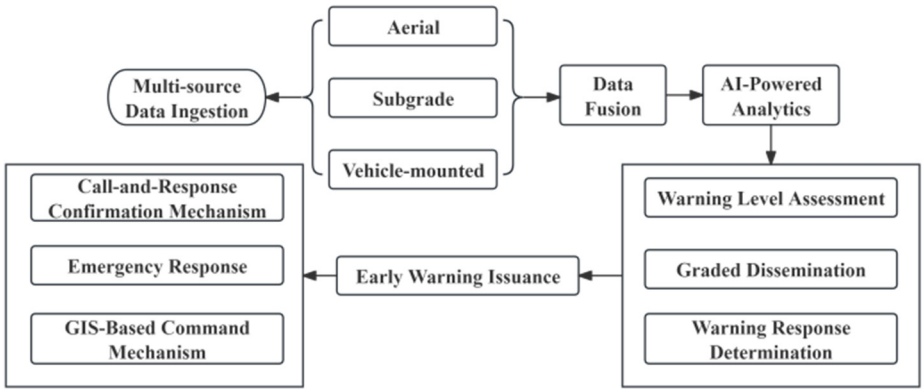


Fig 3. Basic Composition of Data Processing and Early Warning Center

(4) Data Processing and Early Warning Center

The data processing and warning center integrates multi-source heterogeneous data from roadside, airborne, and vehicle-based platforms (visible-light imagery, infrared thermal spectra, 3D point clouds, and sensor streams) via high-speed communication networks. It generates a global structural state map based on a three-level fusion framework: sensor-level, feature-level, and decision-level. It constructs an intelligent bridge risk source identification model using machine learning algorithms, performing real-time matching of historical data with dynamic monitoring information to precisely locate hazards such as crack propagation and deformation anomalies. It pushes graded risk instructions (including location, severity level, and disposal recommendations) to the vehicle-based unit via multi-modal warning channels (SMS/APP/broadcast) to ensure reliable information delivery.

3. Operating Principle of the Air-Ground Integrated Emergency Warning System

(1) Operating Principle of the Subgrade Monitoring Unit

During the data acquisition phase, the system utilizes a coordinated sensor array: a high-definition camera captures real-time visible-light imagery of the bridge structure, while

an infrared thermal imager records temperature distribution patterns and identifies potential defects through thermal signatures. Simultaneously, a laser scanner performs comprehensive bridge surveys to generate precise point cloud data for three-dimensional model reconstruction. The raw data subsequently undergoes systematic preprocessing stages—including noise filtering, artifact removal, and format standardization—before being integrated into a unified multimodal dataset comprising visual, thermal, and spatial information. This processed dataset is then transmitted via robust network infrastructure (4G/5G or fiber optics) to the Data Processing and Early Warning Center. The transmission protocol incorporates advanced encryption for data security, with prioritized data queuing and redundant transmission pathways ensuring reliable delivery of time-critical information.

(2) Operating Principle of the Aerial Monitoring Unit

In routine inspections, the UAV plans flight routes and parameters based on the bridge's structural characteristics and historical monitoring data, conducts autonomous flight along predefined paths, collects high-definition images, infrared thermal images, and point cloud data in real time, and transmits them back to the data processing and early warning center for analysis to generate structural health reports and risk alerts. In emergency response scenarios, upon receiving a report of a sudden bridge incident, the system immediately activates the UAV emergency procedure, selects appropriate UAVs and equipment, and dispatches them rapidly to the incident site. At the site, the UAV provides command coordination, communication relay, and illumination support to ensure smooth rescue operations. For data transmission, 4G/5G or satellite communication is employed to ensure real-time performance, with backup network modes and data encryption functions to guarantee transmission stability and security.

(3) Operating Principle of the Vehicle-mounted Command Center

The Vehicle-mounted Command Center receives encrypted early-warning messages in real time from the Data Processing and Early Warning Center via its integrated radio receivers and mobile communication modules. Utilizing advanced decoding and verification algorithms, it ensures the accuracy and integrity of the incoming data. The intelligent terminal immediately notifies the driver through multi-modal alerts, such as auditory signals and haptic feedback. Should the primary network signal degrade, the system automatically fails over to backup channels, including satellite communication or data transmission radios, to guarantee uninterrupted message delivery. Upon reviewing the warning details on the interface, the driver can promptly acknowledge receipt with a "Confirmed" response and execute necessary maneuvers, including decelerating, changing lanes, or taking a detour. The terminal's intuitive display and interactive design, coupled with its seamless integration with the vehicle's Advanced Driver-Assistance System (ADAS), collectively enhance both operational intelligence and driving safety.

(4) Operating Principle of the Data Processing and Early Warning Center

The early warning mechanism is triggered upon the identification of a risk source. It generates structured alerts containing the risk level, precise location, and recommended response measures. These warnings are disseminated to all Vehicle-mounted Command Centers through multiple parallel channels—including SMS text messages, mobile application push notifications, and broadcast systems—to ensure comprehensive coverage and timely delivery. A robust "call-and-response" confirmation protocol is implemented; if no acknowledgment is received within a specified timeframe, the system automatically re-transmits the alert through alternative communication pathways.

For emergency UAV dispatch, the system initiates an immediate response upon receiving a report of a sudden incident. Suitable UAV platforms are automatically selected based on incident-specific parameters, with continuous real-time communication maintained between operators and the command center to ensure rapid deployment and effective mission execution. During operations, the UAVs continuously collect real-time sensor data while maintaining seamless coordination with the ground command center through persistent data links, thereby significantly enhancing emergency response efficiency and situational awareness.

4. Air-Ground Integrated Early Warning System: Collaborative Mode

(1) Preventive Phase: Multi-Dimensional Monitoring and Risk Prediction

The system establishes a stereoscopic monitoring network through subgrade, aerial, and vehicle-mounted monitoring units, enabling comprehensive dynamic surveillance of bridge structures. The subgrade unit is equipped with high-resolution cameras, infrared thermal imagers, and laser scanners that continuously capture visible-light images, temperature distribution profiles, and point cloud data. The aerial unit utilizes unmanned aerial vehicles (UAVs) to provide flexible coverage of complex terrain areas, generating high-precision 3D models while identifying structural anomalies. Simultaneously, the vehicle-mounted units receive real-time early warning information from the data processing center while contributing vehicle transit data through their onboard sensors. Multi-source data is transmitted to the data processing center via high-speed communication networks and integrated into a unified dataset through sensor-level, feature-level, and decision-level fusion technologies. This integrated approach provides comprehensive dynamic support for risk assessment.

The system employs machine learning models to match patterns against historical incident characteristics, enabling rapid identification of potential risks and generation of early warning information. These alerts are disseminated through multiple channels including SMS, application push notifications, and broadcast systems. A "call-and-response" mechanism ensures reliable information delivery, with automatic switching to backup communication methods when acknowledgments are not received. This integrated mechanism significantly enhances the timeliness of pre-incident warnings, provides crucial technical support for early risk intervention, and effectively prevents secondary bridge accidents.

(2) In-Process Handling: Resource Coordination and Emergency Response

IIn the event of an emergency, the system relies on a unified data processing center to quickly establish a dynamic collaboration mechanism that spans multiple levels and platforms. The aerial unit, via drones, collects multi-dimensional data from the accident scene in real-time and

transmits it back to the center; the base unit activates sound and light alarms and, in conjunction with the laser scanner, generates an information map of the tunnel, assisting with rescue path planning; the vehicular unit receives emergency instructions and coordinates vehicle detours or stops. The data processing center integrates multi-modal data and, using intelligent algorithms, dynamically generates risk levels, location coordinates, and disposal recommendations, while autonomously adjusting the operating modes of monitoring equipment and communication bandwidth allocation, optimizing hardware and energy usage efficiency.

Standardized data interfaces and an open architecture design enable seamless information sharing across multiple units, forming a "perception-decision-response" feedback loop: the early warning center analyzes data in real-time and issues instructions, while the vehicular terminal responds dynamically, and the aerial drones continue to monitor the evolution of the accident. Multi-channel redundant communication and a distributed computing architecture ensure the stability of command transmission in extreme environments, guaranteeing rapid deployment of rescue resources and efficient collaborative operations.

(3) Post-Incident Recovery: Structural Repair and System Optimization

The system supports the recovery of bridge functionality and the upgrade of defense systems through refined monitoring and data analysis. The aerial unit performs three-dimensional laser scanning on the repair area to verify construction quality and monitor the impact of traffic loads on the structure. The base unit tracks the changes in stress distribution within the repair area to assess the effectiveness of reinforcement measures, while continuously collecting temperature, humidity, and corrosion data via environmental sensors. The vehicular unit collects vibration data from vehicles passing through the recovery area, along with driver behavior information, and transmits it back to the center to assist in optimizing the early warning strategy. The data processing center analyzes the accident evolution chain data, optimizes machine learning model parameters and warning thresholds, and generates a digital twin model for structural repair along with system upgrade recommendations. At the same time, it integrates monitoring data from the recovery period with a historical case database to improve the logical rules and response mechanisms for secondary accident defense systems, enhancing the ability to handle similar events in the future and ensuring the long-term safety and stability of the bridge.

5. Conclusion

As a core hub within transportation networks, the safety of bridges is directly linked to the stable operation of the social economy and the protection of people's lives and property. The frequent occurrence of secondary bridge accidents in recent years indicates that traditional monitoring and emergency response systems have significant shortcomings in risk early warning and rapid response capabilities. This paper proposes an air-ground integrated emergency early warning system, which establishes a three-dimensional monitoring network composed of ground-based, aerial, and vehicle-mounted detection units, as well as a central data processing and early warning center, to achieve comprehensive monitoring of bridge structures. The system can accurately assess risk levels through multi-source data fusion during the early stages of bridge damage. When risks such as vehicle collisions or pier damage occur, the system simultaneously activates a series of response measures including drone reconnaissance and traffic diversion, forming an emergency response mechanism of "detection–warning–disposal." The implementation of this system will greatly enhance the intelligence level of bridge safety management, providing strong technical support for ensuring the stable operation of the social economy and safeguarding people's lives and property.

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