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# Deep Learning-Based Highway Rockfall Early Warning System

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**Abstract:** This paper proposes a deep learning-based rockfall warning system for mountainous road curves. It utilizes drone inspections combined with the YOLOv11 object detection algorithm to accurately identify rockfalls on road surfaces, while employing ground-based millimeter-wave radar for real-time vehicle detection. The system features a comprehensive curve blind spot warning mechanism and incorporates a wireless communication module to push instant alerts to mobile navigation terminals based on rockfall risk and vehicle location. This system effectively addresses the challenges of rockfall identification and delayed warnings within blind spots on curves. It reduces manual inspection costs while significantly enhancing driving safety on mountainous roads.

**Keywords:** Deep learning; YOLOv11; Intelligent warning; Highway blind spots; Rockfall hazards

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## 1. Introduction

With the continuous advancement of transportation infrastructure development, mountain roads play a crucial role in safeguarding regional economic growth and facilitating daily life. However, these roads frequently face severe threats from geological hazards, with rockfalls being a common mountainous geological disaster that poses significant risks to transportation infrastructure and driving safety along these routes [1]. On one hand, rockfall disasters are influenced by multiple complex factors such as topography, climate, hydrology, and geological structures, making them prone to collapse during triggers like heavy rainfall or earthquakes [2]. On the other hand, although current mitigation measures include physical protections such as installing protective nets, reinforcing unstable rock formations, and constructing shelters or tunnels, operational management still primarily relies on manual inspections and traditional guarding methods [3].

This approach suffers from high inspection costs and significant risks of missed detections during nighttime or adverse weather conditions. Therefore, developing an efficient intelligent rockfall early warning system is crucial for ensuring driving safety on mountain roads. Against this backdrop, this project designed an intelligent rockfall warning system for mountainous road curves based on the synergy of deep learning and millimeter-wave radar. The system achieves precise identification of road surface rockfalls through drone inspections combined with the YOLOv11 algorithm, while utilizing millimeter-wave radar for real-time detection of ground vehicles. The system incorporates a comprehensive blind-spot warning mechanism for curves, effectively addressing the challenges of rockfall identification and delayed warnings in complex environments. It provides essential technical support for enhancing driving safety on mountainous highways.

## 2. Framework Design

The system comprises an information acquisition system and an alert dissemination system. The information acquisition system monitors rockfall conditions on the road surface, uploading relevant parameters such as geographic coordinates and image features to enable real-time perception of the curve environment while simultaneously transmitting data to the control terminal. The system utilizes aerial drone inspections combined with the YOLOv11 object detection algorithm to accurately identify rockfalls, ensuring the system can detect risks at the earliest possible moment.

The early warning release system, also known as the response system, employs ground-based millimeter-wave radar to continuously track vehicle locations. Upon detecting a vehicle entering a rockfall hazard zone, it immediately pushes real-time alerts to mobile navigation terminals. The control terminal interface displays the precise location of the rockfall, enabling drivers to take evasive action based on the warning information.

Both systems communicate with the edge server via IoT modules. These modules employ wireless communication units capable of handling large data exchanges while minimizing latency. The communication method involves periodically sending heartbeat packets to the terminal server at the application layer to maintain connection vitality and ensure communication reliability.

**Figure 1** illustrates the overall architecture of the mountainous road curve rockfall warning system. It comprises:

(1) Mobile navigation terminals as display units;

(2) Drones and millimeter-wave radars as sensing units;

(3) Edge servers as system control units;

(4) Wireless communication modules as wireless communication and signal transmission units;

(5) Power supply units providing energy to other system components.

The overall system architecture is as follows: the UAV module, wireless communication module, millimeter-wave radar, and camera are each connected to the microcontroller. The power supply unit connects to each sensing module and the microcontroller. The microcomputer and control terminal use the wireless communication module as a bridge to ensure uninterrupted information flow.

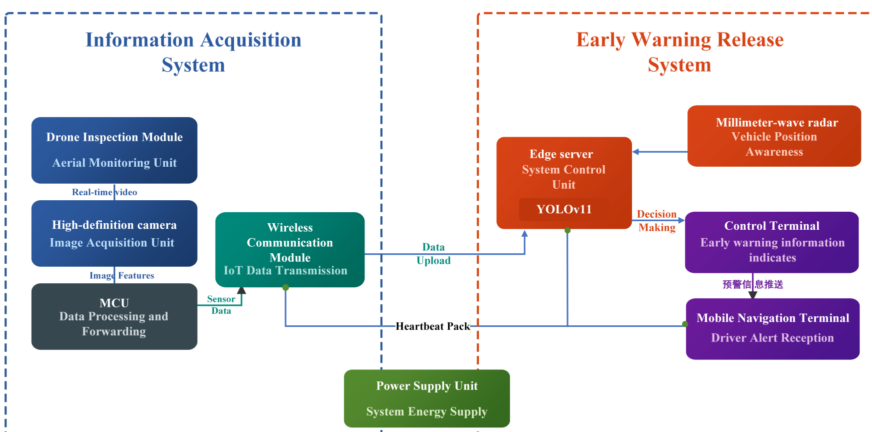


**Figure 1.** Overall framework diagram of the system.

## 3. Methods

### 3.1. Millimeter-wave radar-based vehicle perception

When a vehicle enters a blind spot on a curve, the system uses ground-based millimeter-wave radar to obtain distance information as the primary trigger for early warning. The radar sensor emits electromagnetic waves and receives echoes, using signal processing algorithms to calculate the target's motion state. As the vehicle approaches the curve, the detected distance value gradually decreases. When the target distance signal falls below the safety threshold, the warning monitoring mechanism activates and dynamically responds through the following scheme:

(1) When no vehicles are present within the monitoring area or vehicles are beyond the safety distance, the system enters low-power cruise mode, performing only rockfall environment scans to conserve system energy;

(2) When a vehicle enters the radar detection range, the system immediately activates high-frequency monitoring mode. By integrating real-time rockfall data transmitted from drones, it assesses potential rockfall risks during the vehicle's passage. The system stands ready to send alerts to mobile navigation terminals, prompting drivers to exercise caution regarding road conditions ahead and reducing accidents caused by blind spots.

### 3.2. Deep learning-based precise road-fall identification

Combining the YOLOv11 object detection algorithm with real-time processing of high-definition imagery transmitted from drone inspections, we quantify rockfall risk levels on mountainous road curves. We first collected road surface image data under varying lighting, weather, and terrain conditions, meticulously annotating the location and category of rockfall targets within the images. Next, we employed a pre-trained YOLOv11 model for feature extraction and object detection. By feeding real-time video frames captured by the drone into this model, we obtained rockfall detection results. The system analyzes continuous video streams to filter out environmental distractions like foliage and shadows, precisely identifying anomalous objects on the road surface. Eventually, based on the detected rockfall locations, we determine whether the rocks are positioned along the vehicle's trajectory, thereby enabling real-time road surface rockfall risk assessment.

### 3.3. IoT-based communication establishment and data interaction

The system's communication module employs a combination of IoT technology and TCP/IP protocols for real-time data transmission. First, an edge server is established to connect the wireless communication module with the UAV, radar, and mobile navigation terminals. The UAV serves as the image acquisition terminal, while the radar functions as the vehicle perception terminal. They generate separate data frames containing detected rockfall coordinates and vehicle positions, respectively, transmitting these as data streams via wireless networks to the communication module. The communication module packages this heterogeneous data for transmission to the edge server, where it undergoes fusion analysis. The resulting decision is then pushed to the control terminal. Continuous packet transmission between the communication module, edge server, and all terminals ensures the uninterrupted flow of the data transmission link.

### 3.4. Early warning decision logic

For the early warning system, we fuse the rockfall data detected by drones with vehicle information sensed by millimeter-wave radar on edge servers. The system employs a Kalman filter algorithm to smooth multi-source data, eliminating fluctuations caused by environmental noise. When both conditions, "road surface rockfall present" and "vehicle distance below safety threshold", are simultaneously detected, the system identifies a high-risk state. At this point, the edge server transmits an early warning signal to the mobile navigation terminal via the wireless communication unit.

# 4. Hardware design

## 4.1. Core control and multi-dimensional perception unit

The intelligent early warning system employs a high-performance microcontroller (MCU) as the core unit for on-site data acquisition and processing. This controller features extensive peripheral interfaces and robust data throughput capabilities, enabling concurrent processing of multi-source sensor data. The main control board connects to ground-based millimeter-wave radar and drone-mounted high-definition cameras via high-speed interfaces. The millimeter-wave radar provides real-time vehicle information to the main control board, while the high-definition camera captures real-time road surface imagery. Acting as the central hub of the perception layer, the MCU performs preliminary cleaning and packaging of radar signals and image data based on embedded low-level drivers, establishing a high-quality data foundation for subsequent edge computing and early warning.

## 4.2. Wireless communication and data transmission module

The communication module employs industrial-grade wireless communication units to establish real-time connections between the MCU, edge servers, and control terminals. Data transmission modes primarily include reliable transmission (TCP) and unreliable transmission (UDP). Generally, TCP/IP-based transmission is connection-oriented, providing reliable byte-stream delivery with retransmission mechanisms to prevent data loss. In contrast, UDP transmission is connectionless and broadcast-oriented, offering higher transmission efficiency but carrying a risk of packet loss. Given the mountain rockfall warning system's stringent requirements for safety and data integrity, it is imperative that every warning command is delivered accurately and without error. Therefore, this system adopts the more secure TCP/IP communication method. Additionally, in the application layer design, the communication module periodically sends heartbeat packets to the server to maintain link viability. Should a connection fail, it can immediately reconnect, ensuring extremely high reliability of the communication system.

# 5. Software design

The control terminal features a graphical user interface designed for visual fusion and intuitive interaction with multi-source perception data. Based on the system's deep learning algorithm deployment requirements and hardware characteristics, LabVIEW programming language was selected to develop the warning control software [4]. The intelligent early warning system control software developed based on LabVIEW is a multi-module application. It integrates functional modules such as video stream processing, radar data analysis, risk assessment, and early warning dissemination. This software not only provides managers with a panoramic view of curve safety monitoring but also enables real-time linkage with mobile navigation terminals through backend logic.

## 5.1. Real-time monitoring and visualization interface

The core area of the software's main interface embeds a real-time video window, synchronously displaying high-definition imagery transmitted by drones. After loading the YOLOv11 model, the system performs real-time annotation of identified rockfall targets within the video stream, drawing red bounding boxes and displaying confidence levels. This enables managers to intuitively identify road surface anomalies. The interface sidebar features a radar data visualization panel displaying millimeter-wave radar-detected vehicle distance information as a distance-time curve graph. When a vehicle enters the monitoring range, the system refreshes the relative distance between the vehicle and the blind spot at the curve in real time.

### 5.2. Intelligent early warning mechanism

In the deep learning-based highway curve rockfall warning system, the warning issuance module serves as a critical defense for traffic safety. When the system determines via algorithmic fusion that "rockfall is present on the roadway" and "vehicles are within a hazardous distance," the software automatically triggers a tiered warning process as follows:

(1) Host machine audio-visual alarm: The control terminal interface immediately displays a prominent red warning window showing the rockfall's precise location and the vehicle's current distance, accompanied by an alarm tone. This alerts monitoring center personnel to immediately focus attention and implement emergency measures;

(2) Mobile instant push notification: The software backend invokes network communication interfaces to package the warning information and push it via TCP/IP protocol to the mobile navigation terminals of drivers entering the affected area. The push content includes concise and clear evasion instructions, ensuring drivers receive sufficient reaction time before entering the blind zone, thereby effectively reducing accident risks.

## 6. Conclusion

This paper proposes an intelligent rockfall early warning system for mountainous road curves based on the synergy of deep learning and millimeter-wave radar. The system utilizes wireless communication modules as data transmission tools, connecting the drone inspection terminal, radar sensing terminal, and edge computing server. It employs the TCP/IP protocol to ensure the smooth and highly reliable operation of the early warning link. The system achieves precise identification of road surface rockfalls in blind spots of curves and real-time perception of passing vehicles, enabling instant alerts to be pushed to mobile navigation terminals at the first sign of risk. This design not only significantly reduces the manpower and material consumption required for post-construction maintenance of mountain roads but also technically overcomes the safety bottleneck caused by limited visibility on curves. It promotes the development of traffic geological hazard monitoring toward unmanned and intelligent approaches. In summary, compared to traditional passive protection nets and manual monitoring models, the rockfall warning system designed in this paper demonstrates significant advantages in response speed, detection accuracy, and system coordination. It holds promising application prospects and significant value for widespread adoption.

## Disclosure statement

The author declares no conflict of interest.

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