

Application of Drone Remote Sensing in Fast Detection of Encroachment Threats in the Vicinity of Urban Rail Transit Lines: Use in Emergency Operations

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Abstract. Urban rail transit systems have been the pillar of an urban transportation network, and their safety of operation is critical to the welfare of the populace. Nevertheless, the vast distances and intricate environments through which these rail networks pass are vulnerable to many encroachment risks, such as illegal buildings, fallen trees, landslides, and sinking pipelines and roads. The complexity and fast-changing nature of these threats, coupled with the possibility of sudden occurrence, is a serious problem. Manual monitoring is the main feature of conventional inspection techniques, which are constrained in efficiency, coverage, and data uniformity, making them unsuitable for high-frequency, detailed monitoring. These weaknesses may result in catastrophic outcomes; the failure to identify a hazard on time narrows the time of emergency response, increasing the probability of service failures and accidents. In addition, the absence of unified time and space references makes it difficult to obtain real-time data in emergencies, disrupting command efficiency and responsibility and eventually raising operational costs and weakening the system's resilience.

Keywords: UAV remote sensing, urban rail transit, boundary intrusion hazard, rapid identification, emergency response

1. Introduction

City rail transit systems are a significant component of urban transportation, and it is vital to keep them running to safeguard the life and property of the people in the cities. Nevertheless, because of the complexity of the circumstances in which these networks work and the variety of intrusion threats including illegal construction, as well as natural hazards like fallen trees or land subsidence, they also represent serious direct threats to the safety of the operations [1].

Traditional inspection directives depend heavily upon foot patrol or vehicle patrols. It is constrained by visual constraints, time constraints, and safety considerations of personnel which result in inefficiency, lack of coverage, and irregularity in collecting data under varied standards. Therefore, frequent and small-scale monitoring is a great challenge. Such drawbacks could also be very dangerous because the failure to identify threats early enough might significantly decrease the time available to apply emergency actions, thus making the possibility of disruption of service and accidents more probable. In addition, the absence of unified temporal and spatial frameworks and

inadequate quantitative measurements cause low-quality and incomplete acquisition of on-site information in the wake of unpredictable events, which plays a crucial role in the inefficacy of the decision-making process and responsibility, and finally leads to increased operating expenses and decreased system resilience.

Drone remote sensing technology can be used as a novel solution to these multifaceted issues. This approach involves using low-altitude drones with sensor mounts which are capable of acquiring a large amount of data such as visible light, thermal infrared, and lidar. Photogrammetry and three-dimensional reconstruction methods together allow easy transition between image acquisition and target detection, risk assessment and warning response. A drone remote sensing has incredible advantages over traditional approaches in terms of effectiveness, fastness, cost-effectiveness, and non-physicality of data collection. It is extremely effective in filling gaps in manual inspections and allows inter-departmental data sharing through integration with GIS and operational management systems [2].

The application of drone remote sensing in the field of rail safety has evolved over time with fundamental aerial photography becoming more sophisticated and incorporating multi-sensor systems to develop 3D maps and at the same time moving towards automation systems based on deep learning. The adopted strategy in this paper is systematic which relies on the concepts of technological basis, main application situations, and critical methods. It aims to elucidate the implementation conditions of drone remote sensing in encroachment detection hazards, operational principles of emergency responses, and future directions, offering an overall technical reference to enhance the safety of urban rail transit operations.

2. Principles of drone remote sensing

Remote sensing drones are unmanned aircraft that serve as low altitude aerial vehicles equipped with optical, multispectral, thermal infrared and LiDAR sensors which are used to capture multi-dimensional surface data non-intrusively [3]. Platform and positioning, sensor data acquisition and data processing are the three major components of this technology.

First, drones will fly pre-set flight paths based on GPS/RTK and Inertial Measurement Unit (IMU) technologies to document their position and orientation (POS data) in great detail with the aim of getting precise geographic registration of images. Then, high-resolution cameras may be used by optical cameras; multispectral and hyperspectral cameras may be used to determine vegetation and water spectra; thermal infrared cameras may be used to measure surface temperature; and laser pulses and time-of-flight (TOF) measurements may be used by LiDAR to produce three-dimensional point clouds. Fifth, Structure from Motion (SfM) algorithms are used to match and correct overlapping imagery and reconstruct it into digital orthophotography maps (DOM), digital elevation models (DEM), and other three-dimensional models that can have multiple uses such as mapping, agriculture, or disaster tracking. The whole system conducts efficient and high resolution surveillance of the earth at low altitudes [4].

3. Technical foundations of drone remote sensing for hazard identification

3.1. Drone remote sensing platforms and sensor technologies

Remote sensing using a drone is the main tool in monitoring encroachment threats. Multi-rotor drones (using the vertical take-off and landing method) are appropriate to inspect areas with complex conditions at close range, whereas fixed-wing drones are the best to inspect wide areas at

large distances. The multi-rotor drones have demonstrated great flexibility in terms of mapping studies in mountainous regions since they are able to circumnavigate the obstacles that exist on the rail lines effectively. Urban mapping efforts use lightweight drones with efficient propulsion systems and precise navigation systems to fly at a constant altitude over low-altitude, complex terrains.

Data variety to detect hazards The basis of sensor technology is the data variety required to detect hazards. Visible light cameras are helpful when it comes to detecting obvious hazards including illegal construction and vegetation intrusion [5]. On the contrary, infrared cameras are able to sense thermal abnormalities, which could signify pipe faults and slope distortions. Precise modeling and measuring of distances can be done through LiDAR, which may produce precise three-dimensional point cloud information. There is empirical evidence that a fusion of high-resolution sensors with deep learning algorithms contributes significantly to improving the detection performance in multi-scale target recognition problems. It is interesting to note that research studies on assessing ballastless track fasteners find out that integration of high-definition cameras and LiDAR in drone-based remote sensing devices significantly enhances the precision of minor hazard detection.

3.2. Data processing and analytical techniques

The raw data collected through drone-based remote sensing has to undergo various pre-processing, feature extraction, target detection, and modelling procedures. Image data must be radiometrically and geometrically corrected, and then segmented and matched based on features in order to come up with hazard features. But point cloud data needs to be filtered, registered and stitched together to form powerful three-dimensional models. Using optimised denoising and registration methods, the boundary extraction rate of the rail encroachment is significantly enhanced [6].

The creation of deep learning algorithms has raised the degree of sophistication in detecting hazards. To give an example, more precise multi-scale feature fusion structures have been proposed that are able to work in real time. In addition, multi-factor analyses of drone data remotely acquired using evidence weighting and logistic regression coupling models can be used to provide reliable estimates of the risks of geological disasters. There have been great successes in highway geological disaster screenings using deep learning algorithms, as they automatically recognise slope hazards in images obtained by drones with an efficiency more than three-fold greater than conventional methods.

4. Application scenarios of drone remote sensing in hazard identification

4.1. Identification of overt hazards

Open intrusion threats are easy to detect with visual cameras placed on drones. The high resolution pictures show very distinct edges between objects and their positions, sizes and forms as well as allowing to accurately assess border violations when compared against GIS data [7]. Urban rail transit surveillance programs have shown a broad variety of examples of illegal construction and vegetation encroachments in ordinary drone-captured imagery, suggesting that drones may be useful in surveillance. Tree canopy measurements and horizontal distance measurements to rails can be used to rapidly measure any encroachment threat created by fallen trees, size and location of unauthorized structures, and safety boundary violations. An example would be that since the adoption of remote inspections of the Wenzhou S2 line by drone in December 2024, over 5,000 alerts have been generated. These alerts indicated massive quantities of foreign materials such as

building trash and unauthorized equipment under high structures which caused the maintenance crew to act promptly to guarantee safety.

4.2. Identification of latent hazards

Latent encroachment threat detection needs LiDAR and infrared technologies. Drones equipped with infrared and LiDAR can be flown over roads to survey them in 3D to create models that can measure subsidence, slope displacement, and other parameters with a detection error of 5.38 -7.68 [8]. The usefulness of the railway track subgrade settlement monitoring of LiDAR data has been determined in mountain road mapping. Infrared cameras would be able to identify abnormal thermal emissions of aging or short circuited pipelines prior to critical failures.

4.3. Large-scale hazard assessment and dynamic monitoring

Because of the enormous extent of urban rail transit lines, it is impossible not to carry out regular large-scale hazard assessments. Fixed-wing drones can be more efficient when undertaking broad-line inspections due to their ability to cover more ground and have longer flight times. Multi-rotor drones are, however, very handy when conducting close-up inspections in areas of high value. Integrating satellite and drone remote sensing, satellite imagery can be used to detect large suspect areas, and drone assessments can be performed in particular areas. Small drones can perform full-covert surveillance in one geological disaster emergency investigation, which allows the surveillance in real-time. The approach will greatly enhance the effectiveness of mass, long-range surveillance since the rate of data collection is five to ten times higher than that of the conventional surveying techniques. As an example, the China Academy of Railway Sciences did extensive testing on Hefei-Xuzhou segment of the East China High-Speed Railway using fixed-wing drones that could be launched vertically and survey up to 1,070 kilometers (150 and 200 km per day respectively) with exponential performance over multi-rotor drones and implemented this systematically to reduce external threats to produce an integrated protective system, i.e., air, land, and sea protection [9].

5. Mechanisms of emergency response application

5.1. Rapid location and data transmission of hazards

Drones with remote sensing can be deployed quickly to a place where an unexpected event happens and transmit live visual data to command posts. This property allows rapid deployment and withdrawal, and speedy mapping operations that offer valuable information during disasters. In the event that trees are close to boundaries, drones are able to take pictures and ascertain their position, dimensions and proximity to the rail line which indicates the area where an impact will occur. It is amazing how quickly drone remote sensing may react with no less than a half-hour of data gathering and transfer after the occurrence of an incident.

5.2. Formulation of emergency response plans and effectiveness evaluation

The three-dimensional data gathered by drone remote sensing can also be utilized to model the zones of influence of hazards and aid the stakeholders to formulate reactive plans. Road models and slope models based on drone-derived point cloud data will give accurate data on the area and the intensity of hazardous conditions, and will act as a scientific basis to maintenance operations.

Remote sensing using drones can be implemented after the emergency interventions, and it may be helpful in conducting follow up inspections, as comparative analysis of the data obtained prior to and after the intervention can help assess efficacy [10].

5.3. Collaborative multi-departmental support

Various departments are able to use drone collected information as a remote sensing tool. Once a slope failure has been identified, deformation measurements and images might be integrated with rail transit companies and emergency management agencies to allow rapid action and cooperative relief. Geological disaster monitoring and management systems may help in integrating satellite and drone remote sensing data across various departments and provide technical support to the emergency response.

6. Conclusion

In conclusion, drone remote sensing technology, which has natural benefits in terms of timeliness, spatial resolution, flexibility of implementation, and non-contact inspection, has become one of the main technologies that are used to protect urban rail transit operations.

First and foremost, multi-source sensor fusion approach is much more accurate and profound in the field of hazard detection. The high resolution of visible-light remote sensing enables one to rapidly acquire specific physical properties such as unauthorized structures and fallen trees. Simultaneously, the integration of LiDAR and infrared sensors can be used to fill in the crucial gaps in monitoring concealed hazards, such as subgrade settlement, small slope movement and abnormal thermal emissions of pipelines. The empirical evidence verifies its nature as a non-contact method of remote detection, which perfectly corresponds to the need to carefully inspect the rails and at the same time provides a considerable benefit over traditional surveying in terms of efficiency of data collection.

The other part is the fact that the synergy of integrated aerial-terrestrial systems with intelligent interpretation technologies is an important path to successful long-distance line management. The combination of satellite-based remote sensing of large areas and targeted and specific drone assessments maximizes resources used in monitoring, and deep-learning algorithms also assist in converting human interpretation into automated warnings.

The use of drones in the field shows the high potential of warning mechanisms and closed-loop control mechanisms offered by the remote sensing systems that are used by drones, and that it has the potential to greatly minimize the variety of possible encroachment threats by means of automatic alerts and prompt reactions by the maintenance crew. It is important to note that it assists in ensuring the safety of the railways.

Lastly, in emergency response systems, there is a great potential of using drone remote sensing in managing unexpected scenarios. The rapid deployment and real time images of what is happening on the ground allow command centers to evaluate the situation at the scene fast, forecast the trend of hazard development, and come up with scientifically sound responses. Comparative quantitative analysis of remediation effects may be performed by comparing remote sensing data prior to and after interventions and thus enhancing overall effectiveness of emergency collaboration by improving information sharing between departments and hence increasing the capability of the system to withstand unanticipated incursion incidences.

Outlook: With the further development of multi-source remote sensing data fusion algorithms and the introduction of proper industry standards, the application of drones in remote sensing is expected

to go beyond its niche application and be incorporated into the intelligent management systems of operations. Certain aspects of emphasis should be placed on making sure that the advancement of technology is encouraged with regard to the integration of remote sensing results and the processes and systems of railway transportation and management, which would be crucial in improving the capability of railways to prevent and react to hazards of urban rail transit encroachment and provide scientifically-grounded intelligent technical systems of safe urban rail transit operations.

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