Proceedings of CONF-CIAP 2026 Symposium: Applied Mathematics and Statistics
DOI: 10.54254/2753-8818/2026.CH30913

Application of Remote Sensing Technology in the Construction and Maintenance of Highway and Railway Networks

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Abstract. With the rapid development of China's comprehensive transportation system, the scale of road networks such as highways and railways continues to expand, and traditional ground surveying and inspection methods can no longer meet the current management needs. Remote sensing technology, with its unique advantage of rapidly and accurately acquiring surface information, has become a core technological means to improve the efficiency of transportation infrastructure management. This article provides a systematic review of the application of remote sensing technology throughout the entire lifecycle of highway and railway network construction and maintenance. This paper analyzes multi-source remote sensing technologies such as optics, Synthetic Aperture Radar (SAR), and lidar, and elucidates their key roles in planning and surveying, design and construction, operation monitoring, and disaster early warning. Specifically, it discusses the principles, methods, and related applications of remote sensing technologies from the perspectives of satellite remote sensing and Unmanned Aerial Vehicle (UAV) remote sensing. The collaborative construction of an integrated sky-ground system using satellite remote sensing and drone remote sensing has greatly facilitated the construction and maintenance of road networks. It also points out the inherent limitations of current remote sensing technology at the technical level. The aim is to reveal the comprehensive value and future prospects of this technology in improving the efficiency and safety of transportation infrastructure management.

Keywords: Remote sensing, satellite remote sensing, UAV remote sensing, road network maintenance

1. Introduction

With the rapid development of global transportation infrastructure, highways and railways, as important links connecting regional economies and promoting social exchanges, their construction and maintenance quality is directly related to national economic development and public safety. However, traditional road network surveys have many problems and can hardly meet the needs of modern road network management. Remote sensing technology, with its advantages of non-contact and large-scale monitoring, provides an efficient solution for road network construction and maintenance [1]. In current research, satellite remote sensing (such as the Sentinel series satellites of the European Space Agency, the Landsat series satellites of the United States, and the Gaofen series satellites of China) supports periodic large-scale monitoring for topographic mapping, surface deformation analysis, and land use monitoring [2]. With its high resolution (up to centimeter level) and flexible mobility, Unmanned Aerial Vehicle (UAV) remote sensing focuses on localized fine-grained inspections, such as road surface crack identification and bridge and tunnel detection [3]. The two work together to build an integrated system of sky, air, and ground, and significantly improve the monitoring accuracy through data fusion algorithms (such as improved D-S evidence theory): the plane and elevation errors are controlled at the centimeter level, the crack identification reaches the sub-millimeter level, and the processing efficiency is 20 times higher than that of traditional methods [4,5].

However, the management of these facilities faces many challenges. Therefore, this paper systematically reviews the progress of remote sensing technology in the construction and maintenance of highway and railway networks. It aims to promote the in-depth development of the discipline of transportation remote sensing, and is also of great significance for improving the level of intelligent management of road networks and ensuring transportation safety.

2. Applications of satellite remote sensing technology

2.1. Dynamic monitoring of land use conditions along railway lines

Satellite remote sensing technology has advantages over traditional ground survey methods in the dynamic monitoring of land use conditions along railway lines. Remote sensing technology can comprehensively interpret and analyze the topography, geological structure, ecologically sensitive areas, and existing land use patterns of potential corridors, providing a scientific basis for optimizing route alignment and avoiding major risk sources. During the operational period, it is crucial to continuously monitor land use changes within and around the railway safety protection zone. In recent years, machine learning, especially deep learning models, has greatly improved the automation and accuracy of remote sensing image information extraction. For example, Wang et al. proposed two new models, MFRCNN and SFRCNN, based on Region Convolutional Neural Networks (R-CNN), to detect changes in high-resolution satellite remote sensing images, Their research shows that the proposed new model can automatically and accurately extract land use information such as construction land, farmland, and forest land from high-resolution satellite remote sensing images, The overall accuracy (OA) and Kappa coefficient for extracting image information are 0.9880 and 0.7116, respectively, which are much higher than those of traditional methods and general CNN methods [6]. Fang Yang et al. used remote sensing images and combined them with a proposed change detection model that couples the MAE-Intern Image algorithm to conduct high-precision detection research on changes in the railway surrounding environment [7]. The results show that the proposed algorithm is significantly better than the fully convolutional twin network (Siam-FC) and the dual temporal image transformer (BIT) algorithm in terms of the performance index of detecting changes in cultivated land, forest land, and bare soil. The detection accuracy of changes in cultivated land, forest land, and bare soil is 64.01%, 80.64% and 64.19% respectively [7]. This study provides a reference for accurately identifying illegal land occupation and construction, illegal mining, urban expansion and encroachment, etc., and the relevant models can also realize the efficient quantification of land use patterns along railway lines [7]. A growing body of research indicates that current civilian satellites can achieve a spatial resolution of 0.5 m and an on-orbit repetition time of 1–6 days. Differential interferometric radar technology can even perform millimeter-level monitoring of land subsidence. Combining various new remote sensing technologies with machine learning is an important trend in building an intelligent railway safety monitoring system, and automated perception and risk assessment of the surrounding environment is one of the core links [8].

2.2. Highway infrastructure inspection

As high-standard linear engineering projects, the condition of highway infrastructure directly affects traffic efficiency and safety. Satellite remote sensing technology plays an irreplaceable role in the multi-dimensional monitoring of highway infrastructure.

High spatial resolution optical satellites can enable the identification of road surface conditions and high-precision monitoring of surface deformation where traffic facilities are located, providing effective support for improving road traffic safety. For example, the Gaofen-3 (GF-3) satellite launched in 2016 can acquire microwave remote sensing data with a resolution of 1-500 m and a swath width of 10-650 km under different application modes [9]. In addition, multispectral and hyperspectral remote sensing are also used to detect hidden defects in road surfaces. Asphalt pavements age over time, their spectral characteristics undergo subtle changes. Hyperspectral remote sensing can capture these differences, thus enabling a quantitative assessment of the degree of pavement aging. Jin Xu et al. verified and analyzed the effectiveness of the constructed asphalt pavement health spectral index model based on high-resolution remote sensing data from Worldview-2 (a commercial satellite launched by Digitalglobe) in the Liangxiang area of the Sixth Ring Road in Beijing [10]. By comparing the differences in the aging status of asphalt pavement reflected by different indices, several spectral indices suitable for detecting the health status of asphalt roads were selected [10]. For example, the older the road surface, the greater the change in reflectance in the range of 400 to 900 nm. In the range of 900 to 2100 nm, as the road surface changes from new to old, the slope of reflectance also changes from large to small and from positive to negative [10]. Thermal infrared remote sensing detects localized temperature anomalies caused by road surface defects and combines these temperature difference characteristics with machine learning algorithms to achieve automatic defect identification.

Interferometric synthetic aperture radar (InSAR) is a radar system carried by satellites or drones. InSAR measurement technology uses phase difference to generate surface deformation maps or digital elevation models, and has become a benchmark technology for monitoring millimeter-level deformation of highways and their surrounding areas. Using SAR satellite data such as Sentinel-1 and GF-3, it is possible to obtain surface deformation fields over a wide area with high precision. For example, Xiao Bo et al. first used SBAS-InSAR technology to process Sentinel-1A images covering central Yunnan, obtained the surface deformation and subsidence rate field along the highway, detected potential disaster points along the route, analyzed deformation characteristics, and also used the BP neural network algorithm to establish a prediction model to predict the subsidence trend along the highway. The study found that surface deformation was widespread along the expressway in central Yunnan, with a maximum subsidence rate of -76.50 mm/a. The maximum error between the SBAS monitoring value and the BP neural network prediction value was 0.666 m/a, indicating that the BP algorithm can provide necessary technical support for road disaster identification and survey [11].

2.3. Environmental monitoring along railway lines

By utilizing high-resolution optical imagery and InSAR technology, an integrated technology system of "identification-monitoring-early warning" can be constructed. Optical stereo images can be used to identify the morphological characteristics of disaster bodies, while time-series InSAR can continuously monitor their deformation process, providing crucial information for landslide early warning. For example, researchers such as Zhang Jiajia systematically conducted a geological hazard investigation along the Lancang River section of the Sichuan-Tibet Railway using SBAS-InSAR technology, based on Sentinel-1 and RADARSAT-2 satellite data, in order to comprehensively and accurately obtain information on potential landslide hazards along the route, in order to address such major projects,113 landslide hazard points were identified along the Lancang River section of the Sichuan-Tibet Railway, including 4 densely populated landslide hazard areas and 13 typical landslide hazard points, providing an important reference for the early identification of landslide hazards in the high mountain and canyon areas along the Sichuan-Tibet Railway [12].

3. Application of unmanned aerial vehicle remote sensing technology

As a revolutionary tool for acquiring geographic information, drone remote sensing technology is playing an increasingly important role in the monitoring of railway and highway infrastructure due to its high resolution, flexibility, and cost-effectiveness. By integrating multispectral sensors, LiDAR, and thermal imaging devices, this technology can achieve large-scale, high-precision data collection, effectively overcoming the limitations of traditional manual inspections. Drones, as a platform for remote sensing, provide strong support for the safe operation and maintenance management of transportation infrastructure [13].

3.1. UAV remote sensing application methods

The Land Surface Reflectivity (LSR) method improves satellite spectral reflectance by constructing enhancement factors through the introduction of fractional vegetation cover (FVC) and upscaling UAV data. Based on the spectral unmixing theory, LSR establishes a spectral transformation relationship between the original satellite reflectance and the enhancement factors, playing a crucial role.

Upscaling transformations aggregate high-resolution UAV data to the satellite scale, with commonly used methods including nearest neighbor and pixel aggregation (such as sum aggregation and median aggregation) [14]. For example, in a study of the Jiefang Lock irrigation area, UAV multispectral images (resolution 6.5 cm) were upscaled to 10 m, 20 m, 30 m, and 60 m to match Sentinel-2 and Landsat-8 satellite data [15]. The upscaling process preserves spectral information through a mean aggregation strategy, reducing the impact of spatial heterogeneity.

It also plays an important role in highway and railway construction and maintenance. Variable selection methods, such as Variable Importance in Projection (VIP), are often used to identify sensitive spectral features [16]. For example, in soil moisture inversion, GCD analysis shows that the shortwave infrared band and salinity index have the highest correlation with soil moisture and are used in machine learning algorithms to construct high-precision inversion models [17].

3.2. UAV remote sensing applications

For railway defect detection, UAVs can use high-resolution imagery and deep learning algorithms to automatically identify surface defects on tracks, such as cracks and wear. For example, analyzing track images with the YOLO algorithm achieves a defect detection accuracy of over 90%, more than 40% higher than traditional methods. Multispectral data can also identify ballast loosening and sleeper displacement, providing a basis for preventive maintenance [18].

For along-line environmental monitoring, UAVs equipped with thermal infrared sensors can monitor geological disaster risks in real time, such as landslides and debris flows. In the Jiefang Lock irrigation area, time-series data analysis showed that the settlement rate at nine monitoring points exceeded 20 mm/year, marking them as high-risk zones. Combined with SBAS-InSAR technology, UAV data enabled millimeter-level deformation monitoring, with a warning accuracy rate of 85% [19].

DOI: 10.54254/2753-8818/2026.CH30913

In cadastral management applications, drones can quickly acquire geographic information through aerial photography, assisting in land surveying and mapping. For example, the Shiheng-Canggang Intercity Railway project used drone aerial photography, covering 9 km in a single flight, achieving five times the efficiency of manual methods. Through 3D modeling, a high-precision digital elevation model (DEM) was generated, supporting land use planning [20].

In road surface distress detection, the fusion of multispectral and thermal infrared data can identify cracks, subsidence, and raveling on asphalt roads. At the Shahao Canal test station, drones equipped with LiDAR scanned road elevations, and combined with the ELM model to invert soil moisture, the root mean square error (RMSE) decreased to 0.024, improving accuracy by 13.8%. For instance, after processing point cloud data, the longitudinal elevation measurement error was controlled within 4.38%, significantly outperforming traditional leveling surveys [21].

In infrastructure inspection applications, drones conduct regular inspections of bridges, tunnels, and slopes, integrating research results related to remote sensing upscaling. Structural stability is analyzed through three-dimensional point cloud models. In the Jiefang sluice irrigation area, drones identified multiple hazardous rock slopes, and combined with finite element simulations, they assessed risk levels and guided reinforcement projects. Thermal imaging technology is also used to detect road surface water seepage to prevent water damage [15].

4. Inherent limitations at the technical level

4.1. Data acquisition is severely restricted by environmental and physical laws

Remote sensing technology is highly susceptible to being deceived by the weather. For satellite remote sensing, the quality of optical imaging is highly dependent on good atmospheric visibility. Common weather conditions such as clouds, rain, fog, and snow can all lead to the loss of optical image data or a significant decline in quality. Although synthetic aperture radar (SAR) satellites have a certain penetration capability and can achieve all-weather and all-time observation, the difficulty of data processing and interpretation is much greater than that of optical images, and their spatial resolution is usually low. Therefore, they are inadequate when monitoring "point-like" diseases such as fine cracks and local potholes on the road surface [22]. The operation window for unmanned aerial vehicle (UAV) remote sensing is also strictly limited. High wind speeds, rainfall, and other adverse weather conditions not only threaten flight safety, but also the fuselage shaking and sensor water contact they cause will directly lead to blurred collected images and increased noise in point cloud data, seriously affecting the accuracy of subsequent modeling and analysis [23]. Some studies have pointed out that in mining area applications, thick cloud weather can cause the monitoring accuracy of unmanned aerial vehicles to drop by more than 10%. This conclusion is also worthy of vigilance in traffic inspections.

4.2. It is difficult to balance monitoring accuracy, efficiency, and cost

In practical applications, an "impossible triangle" is often encountered: it is difficult to achieve high precision, high efficiency, and low cost simultaneously.

To achieve centimeter-level or even millimeter-level high-precision monitoring (such as identifying fine cracks on the road surface), drones are often required to fly at low altitudes and low speeds. However, this significantly reduces the coverage of a single operation, leading to low efficiency and generating a vast amount of data, which brings huge pressure to subsequent transmission, storage, and processing. Conversely, although using satellites for large-scale rapid coverage is highly efficient, their resolution is difficult to meet the demands of meticulous maintenance. In addition, high-precision sensors (such as LiDAR and hyperspectral imagers) are usually large in size, heavy, high in power consumption, and expensive. This poses a huge challenge

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for unmanned aerial vehicle (UAV) platforms that pursue lightweight and long endurance, restricting their widespread application on a larger scale [23].

4.3. The dilemma of data processing and intelligent interpretation

The core of building an integrated monitoring system covering sky, air, and land lies in data integration, but this is precisely the technical difficulty. The data obtained by satellites, unmanned aerial vehicles, and ground sensors vary greatly in resolution, phase, coordinate system, and format. Effective integration of them is like compiling reports written in different languages and standards into a unified document, which requires complex coordinate unification, scale matching, and information extraction. Although some studies have adopted advanced algorithms such as the improved D-S evidence theory for data fusion and achieved certain results, the universality and degree of automation of these methods still need to be improved. Remote sensing data from different sources are difficult to integrate seamlessly, and the phenomenon of "data silos" has not been completely solved, which restricts the maximization of the effectiveness of integrated monitoring. At present, the automatic identification of diseases based on artificial intelligence (AI) (such as identifying cracks and settlement) is a research hotspot. However, the performance of AI models heavily relies on a large amount of high-quality, precisely labeled sample data for training. In practical applications, models are prone to interference from factors such as changes in light, obstructions of objects, and complex backgrounds (such as road shadows and vegetation), leading to misjudgments or missed judgments.

4.4. Economic costs and the realistic barriers of airspace management

A complete solution that includes high-performance drones, lidar, high-precision POS systems, and professional processing software is quite expensive. At the same time, it also requires a significant investment to cultivate or hire compound technical talents who are proficient in both remote sensing technology and transportation engineering. For many local units or small and medium-sized enterprises with limited maintenance budgets, this initial investment constitutes a relatively high threshold. Especially along railways and busy highways, the flight of drones is subject to strict airspace control. For instance, the state has issued airspace usage restrictions strictly prohibiting unmanned aircraft from flying within specific areas of railway lines, which has greatly restricted the application of drones in railway line inspections. The approval process for flight missions is complex and time-consuming, which also restricts the response speed of emergency inspections. In addition, when flying near expressways, the potential safety risks to passing vehicles must also be fully considered, and the operation plan needs to be extremely cautious. Even if the problem of a single technology is solved, integrating multiple technologies, such as satellites, unmanned aerial vehicles, and ground Internet of Things, organically into a stable and efficient integrated monitoring system still faces challenges. This involves the unification of communication protocols, data interfaces, and platform architectures among different devices. At present, there is no unified standard for determining the boundary points of multi-source remote sensing data fusion [24]. How to achieve real-time linkage and intelligent decision-making of "space-air-ground" data and form a closed loop of monitoring-analysis-early warning-maintenance still requires continuous exploration at the system integration level.

5. Conclusion

This article conducts a systematic analysis of the bottlenecks faced by satellite and unmanned aerial vehicle remote sensing technologies in the practical application of highway and railway network construction and maintenance. It can be seen that although the integrated monitoring model of "sky,

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air, and land" represents the future development direction, its large-scale and regular application still faces a series of severe challenges from technology to management. Remote sensing technology has inherent limitations at the level of data acquisition. Whether it is the vulnerability of satellite optical images to weather interference or the strict requirements of unmanned aerial vehicle (UAV) operations for meteorological conditions, all these indicate that the current remote sensing technology is still unable to achieve truly all-weather and full-time reliable monitoring. The accuracy, efficiency, and cost of monitoring are difficult to balance, forming an unavoidable "impossible triangle" in practical applications, which restricts the popularization of the technology in scenarios that require both high precision and high efficiency.

At the level of data processing and interpretation, bottlenecks are equally prominent. Meanwhile, the accuracy and robustness of intelligent interpretation models based on artificial intelligence in real and complex scenarios are still insufficient. Their performance is highly dependent on high-quality labeled data and is difficult to completely replace human experience-based judgment. In addition, the high overall cost and strict airspace control constitute a realistic barrier that cannot be ignored for the implementation of the technology. This not only includes the expensive investment in hardware and software, but also the cost of cultivating versatile talents, and at the same time, the safety and regulatory risks faced when conducting flight operations near major traffic arteries must also be taken into consideration. Looking ahead, the process of overcoming these challenges is precisely the process of promoting the maintenance of highways and railways from the traditional model to a new stage of digitalization and intelligence. Although there is no shortage of challenges ahead, remote sensing technology will undoubtedly become the core driving force for building a safer and smarter transportation network.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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