

Exploring the Application of Remote Sensing Technology in Highway Management and Maintenance

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Abstract:

In the context of a substantial surge in demand within the transportation industry, the challenges associated with traditional road maintenance have increased significantly, accompanied by high labor costs. In response to this situation, this paper presents the main applications of remote sensing technology in highway management and maintenance and discusses some deficiencies of remote sensing technology in road monitoring. Remote sensing technology, with its efficient and comprehensive information acquisition capabilities, can effectively make up for the limitations of traditional road monitoring methods in terms of timeliness and coverage, thereby enhancing road management efficiency and promoting the modernization of management approaches. This paper demonstrates the feasibility of remote sensing technology in three aspects: the detection of highway networks, the monitoring of the degree of road damage caused by natural disasters, and the real-time monitoring of road traffic conditions. It is proven that remote sensing technology can bring about substantial transformations to road management approaches.

Keywords: The transportation industry, Road maintenance, Remote sensing technology

1. Introduction

Highways play an important role in the development of modern society. Highways, as the most fundamental transportation facilities, connect various modes of transportation and greatly facilitate people's travel and the transportation of goods. The coordinated development between highway construction and economic society has fostered sustainable development and enhanced the overall efficiency of transportation.

The rapid expansion of the highway network has alleviated the problem of transportation tension, but at the same time, the excessive road network has brought great trouble to the management and maintenance of highways, and added difficulty and complexity to future road planning.

Traditional approaches predominantly rely on manual means for road management and monitoring. Relying solely on manual labor for road management and monitoring not only entails substantial costs, consum-

ing a significant amount of human and material resources but also suffers from low efficiency. As a result, it is infeasible to monitor the real - time status of various roads. In the face of secondary disasters to roads caused by natural disasters such as snowstorms, floods, mudslides, hailstorms and sandstorms, if the damage to the roads cannot be obtained in time, it may bring safety hazards to vehicle travel. Between 2001 and 2007, approximately 30% of traffic accidents on China's expressways were directly related to adverse weather conditions each year [1]. The number of casualties in traffic accidents under adverse weather conditions accounted for about 20% of the total number of casualties [1]. In contrast to traditional manual inspection methods, remote sensing technology exhibits greater advantages in road monitoring. For instance, the combination of remote sensing technology and vehicle trajectories can effectively obtain road information. Bai et al. achieved another major breakthrough by integrating remote sensing images with vehicle trajectory data to generate road networks. By merging mobile - based data and image - based segmentation, their method rectified the inconsistencies in road mapping and improved the accuracy of road connectivity.

To solve such problems and achieve rapid monitoring of road conditions, this paper proposes that high-resolution remote sensing images combined with unmanned aerial vehicle (UAV) technology can be used to monitor roads. With the continuous maturation of China's high-resolution remote sensing technology, the quality of images captured by domestic satellites has approached the international leading level [2]. Consequently, high-resolution remote sensing technology holds a high degree of feasibility in areas such as road monitoring and natural disaster monitoring. The development of unmanned aerial vehicle (UAV) technology enables it to make up for the shortcomings of satellite remote sensing and achieve real-time earth observation at the lowest cost. Regarding the application of remote sensing technology in the road traffic industry, this study conducts research from three aspects. Specifically,

it presents the applications of remote sensing technology in the investigation of highway network conditions, the monitoring of the degree of road damage inflicted by natural disasters, and the real-time monitoring of road traffic operation status.

2. Common remote sensing methods in highway maintenance and management

High - resolution remote sensing technology pertains to the technique of acquiring remote sensing imagery and associated data of the Earth's surface with high spatial resolution, high spectral resolution, or high temporal resolution. This is accomplished through high - performance sensors mounted on satellites, aerial platforms, and other carriers. The central aim of this technology is to achieve precise Earth observation, thereby offering more accurate data support for various domains, including resource exploration, environmental monitoring, and disaster emergency management. In the realm of road monitoring, high - resolution remote sensing technology can precisely identify pavement cracks by high - resolution imagery. By integrating multispectral and synthetic aperture radar (SAR) technologies, it is capable of achieving all - weather monitoring.

Unmanned Aerial Vehicle (UAV) remote sensing is a technology that employs UAVs to carry sensors for acquiring ground or environmental information. Integrating remote sensing, navigation, and data processing technologies, it enables rapid and highly accurate monitoring and analysis of the target area. This approach has significantly enhanced our capabilities in gathering detailed data about various landscapes and environmental conditions, providing valuable insights for numerous applications across different fields. Table 1 is a comparison of various remote sensing methods:

Table 1 Comparison of various remote sensing methods

Characteristics	Unmanned Aerial Vehicle (UAV) remote sensing	Satellite remote sensing	Human-machine remote sensing
Resolution	Centimeter level	Metre to sub-metre	Sub-metre to centimeter
Revisit cycle	On-demand (minute-level response)	Hours to days	Need to plan ahead
Costs	low	High (Commercial satellite data)	high
Applicable scenarios	Small range, fine monitoring	Large-scale, periodic monitoring	Medium to large-scale, specialized tasks
Weather Effects	Limited by strong winds and rainfall	Affected by clouds	Affected by airspace control

3. The application of remote sensing technology

3.1 . The Application of Remote Sensing Technology in the Investigation of Highway Network Conditions

High-resolution remote sensing image data can provide accurate and intuitive data information for aspects such as land occupation analysis, geological investigation, and construction drawing production in the planning of highway networks [2]. The application of high-resolution remote sensing can render mapping more accurate and comprehensive in information coverage. Thus, high-resolution remote sensing data serves as the primary data resource during the pre-construction phase of highways.

High-resolution remote sensing technology can also be applied to geological exploration. High-resolution remote sensing data enables the extraction of precise data and information regarding geology, topography, and geomorphology. It can identify unfavorable geological conditions, special geological features, etc., thereby providing a theoretical foundation for route selection, as well as the siting of bridges and tunnels during road construction [2].

High - resolution remote sensing technology also finds significant applications in the calculation of engineering quantities. Based on the data provided by high - resolution remote sensing imagery, the length and width of the roads requiring construction can be estimated in conjunction with topographic maps [2]. Through dynamic comparisons between remote sensing imagery and other relevant data sources, it is possible to estimate the engineering quantities of highways, bridges, and tunnels. This approach enables the timely monitoring of construction progress [3] and the prediction of the construction completion time.

3.2 . The application of remote sensing technology in monitoring the extent of road damage caused by natural disasters

In some areas, natural disasters occur frequently. Affected by natural disasters, roads may be damaged to a certain extent. By using high-resolution satellite remote sensing and unmanned aerial vehicle (UAV) remote sensing in combination, the affected areas can be determined on a macro level [3]. At the micro level, by making use of the captured high - resolution images, it is possible to detect the minute cracks that occur in roads and bridges due to the impacts of earthquakes and other factors [4]. Enabled by remote sensing technology, technicians are able to acquire the damage status of road surfaces more rapidly. Moreover, they can promptly devise timely remedial mea-

sures according to the data provided by remote sensing imagery [5].

In addition, in areas with cold climates, icy roads are a common problem. In the process of detecting ice layers on roads, unmanned aerial vehicle (UAV) remote sensing is an important technical solution. Unmanned aerial vehicles (UAVs) acquire temperature data of the road surface by being equipped with infrared cameras. If the temperature of a specific road section is significantly lower than that of other areas, this section is likely to be icy [6,7]. By integrating remote sensing data with meteorological data and road surface sensors, road technicians can accurately obtain the road icing conditions and issue timely warnings, significantly reducing traffic accidents caused by road icing.

3.3 . The Application of Remote Sensing Technology in Real-time Monitoring of Road Traffic Operation Conditions

In recent years, with the rapid development of the transportation industry, the traffic volume in China has increased significantly, resulting in traffic congestion in some regions. Especially after natural disasters occur, the traffic capacity of vehicles weakens and the traffic flow undergoes significant changes[2]. Traditional traffic flow detection methods are achieved by installing traffic flow detection equipment on the road surface or beside the road. Traditional traffic flow detection can be classified into two categories: fixed-type and mobile-type. The fixed - type detection is generally carried out through remote microwave, ultrasonic waves, infrared rays, etc. The mobile - type detection involves traffic flow detection devices based on GPS (Global Positioning System) and electronic license plates, etc[8]. Both are methods used in traffic flow detection, but they also have their limitations. The fixed - type detection method incurs high costs and is not easy to maintain. As for the mobile - type detection method, since not all vehicles are equipped with GPS, it is difficult to obtain accurate data [8]. Therefore, it is proposed to utilize remote sensing technology for the real - time monitoring of road traffic operation conditions.

Remote sensing technology typically identifies vehicles by discerning their external features. This identification approach can be classified into two categories: explicit identification and implicit identification [9]. Explicit identification generally represents vehicles using bounding boxes and determines whether an object is a vehicle by comparing it with a pre - established model. Implicit identification, on the other hand, conducts detection by examining the differences in the feature vectors of image pixels surrounding the vehicle [9,10].

Compared with traditional detection technologies, unmanned aerial vehicle (UAV) remote sensing can achieve real-time detection of traffic flow without damaging the ground. Moreover, it has low cost and is easy to maintain, making it one of the important means of traffic flow detection at present.

4. Suggestions and Prospects

There remains substantial scope for the advancement of remote sensing technology in the domain of road management. The pursuit of intelligence represents a pivotal area of research for the future development of remote sensing technology. To achieve the intelligence of remote sensing technology, it is necessary to integrate data from satellites, unmanned aerial vehicles (UAVs), ground sensors and the Internet of Things, and establish a “digital twin” platform for road management. In conjunction with artificial intelligence technologies, leverage machine learning models to analyze remote sensing big data, enabling the prediction of road service life and the optimization of maintenance budget allocation.

In the context of integrating intelligent transportation systems, the integration of remote sensing data and automotive sensors enables the analysis of regional traffic flow and congestion patterns. Looking ahead, high-precision remote sensing maps can be utilized to furnish autonomous vehicles with real-time road condition information, thereby realizing seamless vehicle-road collaboration.

Despite the application and popularization of remote sensing technology in traffic management, there are still some shortcomings, such as the high cost of high-resolution remote sensing data, which requires the promotion of low-cost small satellites and unmanned aerial vehicle (UAV) technology; the data processing algorithms in complex environments still need to be optimized, etc. The deployment of low-cost remote sensing platforms and the optimization of algorithms under complex conditions will be the crucial breakthrough points in the future development of remote sensing technology.

5. Conclusion

This paper summarizes the prevalent applications of remote sensing technology in the management and maintenance of highways. Having undergone continuous development, remote sensing technology has now reached a high level of maturity. The utilization of high - resolution remote sensing for the investigation of highway network conditions can offer accurate data resources for highway cartography. This approach enables the avoidance of unfavorable geological conditions and the selection of the op-

timal construction plan. By acquiring engineering quantity data via high - resolution remote sensing technology, the degree of control over the construction progress has been significantly improved. Regarding road damage caused by natural disasters, high - resolution remote sensing imagery can promptly detect minute cracks that occur on roads, as well as the ice layer on the road surface during ice and snow weather conditions. By leveraging the data acquired through remote sensing, personnel can implement timely remedial actions. This effectively reduces the likelihood of accidents and averts unnecessary casualties. Ultimately, this study elucidates the limitations of conventional methods for measuring traffic volume. Additionally, it presents the approaches for vehicle identification enabled by remote sensing technology and the merits of employing remote sensing for traffic volume measurement. The integration of unmanned aerial vehicle (UAV) remote sensing and satellite remote sensing can reflect road conditions in real time. Nevertheless, under certain extreme weather conditions, UAVs may not be able to take off. Consequently, there will be an excessive dependence on satellite remote sensing, which may cause untimely acquisition of remote sensing data. In future research endeavors, the realization of real-time remote sensing under extreme weather conditions merits significant attention.

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