Designing an Intelligent Pavement Maintenance and Management System using Drone Imagery and Artificial Intelligence

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Abstract: This paper presents the development of an innovative pavement maintenance and management system leveraging advanced drone imagery and Convolutional Neural Network (CNN) image classification. Our system is designed to perform 2D modelling of road surfaces using high-resolution images captured by drones. These images are then analysed by a CNN model specifically trained to detect and classify pavement damages in accordance with the IRC:82 'Code of Practice for Maintenance of Bituminous Surfaces of Highways'. The classification process identifies various types of road distresses such as cracks, potholes, and surface wear. Each identified distress is documented in a comprehensive report detailing the nature of the damage and recommending specific remedies as per IRC guidelines. Furthermore, the system categorizes the severity of the damages, facilitating the dispatch of these results to maintenance authorities for immediate action. This ensures that repair efforts are prioritized effectively, contributing to the maintenance of safer and higher quality roadways. By automating the detection and classification of road damages, this system not only accelerates the repair process but also plays a crucial role in reducing road accidents by maintaining better road conditions. This approach showcases the potential of integrating artificial intelligence and drone technology in the field of road maintenance, marking a significant step towards smarter and safer road infrastructure.

Keywords: Pavement maintenance and management system; Drone imagery; Convolutional Neural Network (CNN); IRC guidelines; Automating the detection and classification of road damages.

1 Introduction

This paper introduces a comprehensive system poised to modernize pavement maintenance through the integration of drone-captured imagery and Convolutional Neural Network (CNN) image classification. Addressing the critical need for infrastructure maintenance, the proposed system capitalizes on the agility of drone technology and the analytical prowess of CNNs to offer a robust solution for road surface analysis. By transcending the limitations of traditional maintenance methodologies, this system not only enhances the accuracy and efficiency of inspections but also significantly reduces the time taken to respond to and repair pavement damages. The utilization of high-resolution

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drone imagery provides a detailed view of current road conditions, while the advanced CNN model interprets these images to identify and classify damage accurately. This fusion of technology is a proactive step towards maintaining road infrastructure and ensuring safety. The innovative approach detailed in this paper could potentially redefine standard maintenance protocols by offering a scalable, cost-effective, and technologically driven maintenance and management system. By automating critical processes and employing machine learning for image analysis, the system sets the stage for a new era in pavement maintenance where decision-making is data-driven and pre-emptive rather than reactive. This paper will elaborate on the system's design, its implementation strategy, and the potential impact on current maintenance practices, aiming to demonstrate the viability and necessity of such a system in today's context.

1.1 Evolving Challenges in Pavement Maintenance

The field of pavement maintenance is grappling with contemporary challenges, including increased traffic volumes, budgetary constraints, and the urgent need for stable practices. Conventional methods, while having served in the past, are inadequate in addressing the complex demands of modern road infrastructure. This inadequacy not only leads to inflated maintenance costs but also compromises road safety, necessitating a re-evaluation of existing strategies and the adoption of more technologically advanced and efficient approaches (Miller, 2003; Newman, 2012) [1] [2]. Makendran et al., (2021, 2022, 2015, 2020, 2018, 2023, 2022) developed pavement distress models for road management systems [21] [22] [23] [24] [25] [26] [27].

1.2 The Critical Role of Road Infrastructure

Road infrastructure plays a crucial role in economic development, environmental sustainability, and public safety. Efficient and effective management of road networks is essential for fostering economic growth, reducing environmental impacts, and ensuring the safety of the public. The sustainability of urban development hinges on the ability to maintain and improve road infrastructure in a way that meets these diverse and often competing demands (Ivanova, 2013; Haasis, 2020) [3] [4].

1.3 Advances in Pavement Monitoring Technology

The last decade has seen significant advancements in pavement monitoring technologies. Innovations such as the integration of IoT sensors, GIS, and machine learning have transformed traditional maintenance methodologies. These technologies facilitate enhanced data collection and analysis, enabling more accurate and predictive maintenance strategies. This evolution in pavement monitoring is a testament to the increasing reliance on technology to meet the growing demands of road maintenance and management (Rasol, 2022; Elhadi, 2009) [5] [6].

1.4 Drone Imagery in Pavement Inspection

The adoption of drone technology in pavement inspection marks a significant step forward in the field. Drones, equipped with state-of-the-art imaging technologies, provide an unparalleled view of road surfaces, revealing details that are often missed in conventional inspections. This method not only enhances the accuracy of inspections but also streamlines the process, making it more efficient and cost-effective. The comprehensive data collected by drones is instrumental in identifying potential issues before they escalate, thereby reducing the overall maintenance costs and road closure times (Puppala, 2020; Outay, 2020) [7] [8].

1.5 CNN in Pavement Damage Classification

The application of CNNs in pavement damage classification represents a significant leap in automated road maintenance. Trained on extensive datasets, these neural networks are adept at identifying and categorizing various types of road damages, from minor cracks to major potholes. This capability not only improves the accuracy of damage assessment but also accelerates the maintenance process, allowing for more timely and effective interventions. The use of CNNs in this context demonstrates the potential of AI in transforming traditional pavement maintenance practices, offering a more proactive and data-driven approach (Maeda, 2018; Elghaish, 2022) [9] [10].

1.6 Research Gap

In most of the previous research and studies regarding road maintenance, involves selection of roads for monitoring, collecting the distress survey by using drones manually, and prepared report is sent to the Road Maintenance Authorities by conventional methods. Though by these conventional methods, the problem is addressed but it takes a huge amount of time in resolving the problem. Our goal is to minimize the time by using Artificial Intelligence in the drone and using image classification to find the type of cracks, Calculating each distress of sections and percentage of road failures. The information is sent to the road engineer on a day-to-day basis through email and SMS.

1.6.1 Response Time Challenges in Conventional Road Maintenance

In traditional approaches to road maintenance, a significant research gap exists concerning the time-consuming processes involved in distress survey, data collection, analysis, and report preparation. The conventional method of manually monitoring selected roads using drones and subsequently sending distress reports to Road Maintenance Authorities has proven effective but suffers from considerable delays in problem resolution. This subsection aims to delve into the inherent challenges posed by the delayed response times in the existing maintenance paradigm. We explore the implications of this time delay on road safety, infrastructure integrity, and the overall efficiency of the maintenance process. The objective is to highlight the critical need for a more time-efficient solution, emphasizing the potential impact on minimizing road failures and ensuring safer and more resilient roadways.

1.6.2 Transitioning Towards Instantaneous Pavement Failure Monitoring

Addressing the identified research gap involves a paradigm shift from the conventional approach to an intelligent pavement management system. By incorporating Artificial Intelligence (AI) into drone technology and utilizing image classification, the goal is to revolutionize distress identification, calculation, and reporting processes. The proposed system aims to achieve immediate and automatic monitoring of pavement failures, ensuring a proactive response to emerging issues. This section discusses the specific mechanisms through which AI and image classification contribute to this transition, emphasizing their role in expediting distress identification, calculating distress severity in road sections, and providing real-time data to road engineers. Additionally, the subsection highlights the potential benefits of this transition, including enhanced road safety, reduced maintenance costs, and the overall efficiency of road infrastructure management.

1.7 Methodology

The working methodology of designing an intelligent pavement maintenance and management system using drone imagery and artificial intelligence is given below in the methodology chart (Figure 1).

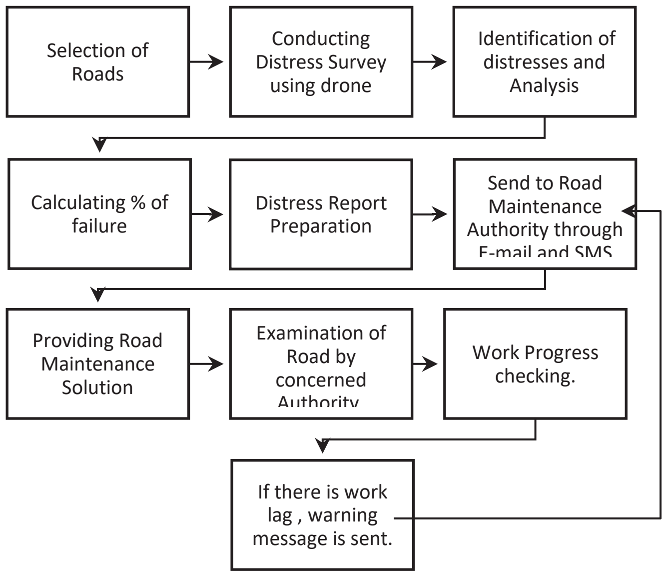

Figure 1: Methodology Chart

2 Intelligent Pavement Management System

2.1 The Historical Context and Evolution of Pavement Maintenance

Pavement maintenance techniques have developed significantly over the centuries, adapting to the increasing demands of transportation. The genesis of organized roads can be traced back to the Carthaginians around 600 B.C., with the Romans later developing an extensive road network to facilitate military movements, establishing principles of road construction that would endure for centuries (Tillson, 1900) [11].

During the Telford and Macadam era, Thomas Telford and John Macadam made significant contributions to road design. Telford's designs, characterized by flat grades and three-layered pavement sections, were notable for their depth and load-supporting capability (Collins and Hart, 1936; Baker, 1903) [12] [13]. Meanwhile, Macadam's approach involved the use of angular aggregate for better performance and drainage, marking a shift to the modern concept of pavement layering (Smiles, 1904; Gillette, 1906) [14] [15].

By the turn of the 20th century, there was a noticeable reduction in pavement thicknesses from the earlier substantial Roman designs to more measured approaches like Macadam's, reflecting an evolving understanding of material efficiencies and structural requirements (Gillette, 1906) [15]. This historical progression underpins today's sophisticated pavement maintenance strategies, which continue to integrate past wisdom with contemporary technological advancements.

2.2 Previous Studies on Pavement Distress Identification

Unmanned Aerial Vehicles (UAVs) have been increasingly adopted for identifying pavement distress. A study conducted by Li et al. (2023) [16] demonstrated the effectiveness of UAV light detection and ranging (LiDAR) with random forest algorithms to accurately assess road conditions. This technology significantly enhances the precision of pavement distress identification while minimizing the reliance on manual surveys (Li, Z., Cheng, C., Kwan, M.-P., Tong, X., & Tian, S., 2023) [16].

Another research initiative by Cheng et al. (2023) [17] focused on the autonomous detection of pavement distress. Drones were programmed to autonomously survey roads, diagnose distress in real-time, and pinpoint exact locations needing repair. This method offers a faster, more efficient alternative to traditional inspections, reinforcing the potential of UAVs in advancing pavement maintenance strategies (Cheng, D., & Lane, L., 2023) [17].

2.3 Use of Drone Technology in Pavement Maintenance

The advent of drone technology has significantly enhanced pavement maintenance strategies. Drones, equipped with high-resolution cameras and advanced sensors, offer a rapid and efficient means of surveying vast road networks. They have revolutionized the way pavement conditions are documented, communicated, and analysed. Cheng and Lane's (2023) [17] comprehensive study illustrates the practical application of drones in evaluating pavement conditions. Their research, which encompasses three case studies, underscores the increased speed and precision of data capture facilitated by drones. The ability to process and analyse this data remotely streamlines the identification of pavement distresses, enabling prompt and informed maintenance decisions. Such technological advancements are vital in the upkeep of road infrastructure, ensuring safety and prolonging the lifespan of transport pathways.

2.4 Advancements in Image Processing for Pavement Analysis

The application of image processing in pavement analysis has seen significant advancements over the past decade, with innovative methods emerging to enhance the accuracy and efficiency of pavement condition assessments. Among these, the implementation of Unmanned Aerial Vehicles (UAVs) coupled with sophisticated image processing algorithms marks a transformative step in pavement maintenance strategies. Traditional manual surveys, constrained by the labour intensity and subjectivity, are progressively being supplemented by UAV-based methods that offer comprehensive, rapid, and objective assessments of pavement conditions.

Utilizing UAVs for capturing high-resolution aerial imagery enables detailed 2D and 3D modelling of road surfaces. These models serve as a robust platform for the interpretation of pavement distresses, allowing for precise measurements of damage dimensions without the need for on-site manual surveys. Astor et al. (2023) [18] have notably contributed to this field by integrating the Surface Distress Index (SDI) and Pavement Condition Index (PCI) methods with UAV-acquired models, comparing their efficacy against traditional field assessments. Their research underscores the higher precision and reliability of the PCI method when applied to UAV-derived pavement condition models.

The comparative accuracy of pavement distress dimensions in UAV-based models against manual field measurements reveals a significant correlation, with edge cracking and joint reflective cracks achieving the highest accuracy values. Moreover, the research by Astor et al. (2023) [18] establishes a robust linear regression equation for the PCI method in

UAV models, reinforcing the potential of UAV technology in automating and refining pavement condition surveys.

This integration of UAV technology and image processing heralds a new era in pavement maintenance, where the rapid identification and classification of road distresses can be achieved with unprecedented precision and speed. The implications for road safety and maintenance efficiency are profound, setting the stage for intelligent pavement management systems that can respond proactively to the ever-evolving demands of road infrastructure preservation.

2.5 Integration of AI in Road Infrastructure Management

Artificial Intelligence (AI) is steadily reshaping the landscape of road infrastructure management, bringing about a paradigm shift from traditional reactive approaches to proactive, predictive methodologies. AI's role in enhancing the resilience and efficiency of road networks is underscored by the work of Phusakulkajorn et al. (2023) [19], who provide a comprehensive review of AI applications in railway infrastructure, which closely parallels road management. Their study highlights the growing number of contributions in the field, showcasing AI's capability to address complex technological challenges and adapt to diverse infrastructure needs. By reviewing key AI methodologies and their applications in infrastructure, the research illuminates the transformative impact of AI, from improving operational efficiency to advancing sustainable development goals within the transport sector.

2.6 Potential for Automation in Pavement Maintenance

The integration of automation in pavement maintenance heralds a significant shift from conventional manual surveys to more sophisticated, data-driven approaches. A pivotal study by Li et al. (2022) [20] details an automated decision-making system in highway pavement preventive maintenance that employs deep learning. This innovative system proposes a predictive maintenance strategy for highway mileposts, which enhances the decision-making process by accurately identifying and prioritizing maintenance tasks, thereby streamlining the entire maintenance workflow (Li, J., Yin, G., Wang, X., & Yan, W., 2022) [2].

Building upon this, another research highlights the benefits of deep learning in automated decision making for highway pavement preventive maintenance. The research accentuates how these intelligent systems lead to more accurate identification and prioritization of maintenance needs, representing a step forward in the efficiency and effectiveness of pavement maintenance strategies. Moreover, a comprehensive review of pavement asset management systems accentuates the profound impact of transitioning to automated pavement condition surveys. This shift has greatly improved the rate of data collection and the subsequent analysis, enabling a more cost-effective and extensive monitoring of pavement conditions. Such advancements are crucial in overcoming the limitations of manual data collection methods and in advancing towards a more robust pavement asset management approach. These citations collectively illustrate the ongoing transformation in the pavement maintenance sector towards automation and predictive analytics. This transition is not merely about the adoption of new technologies but represents a fundamental change in how pavement maintenance is conceptualized and executed, promising increased efficiency, safety, and longevity of road infrastructures.

2.7 Comparative Case Study:

Comparison is done between results of pavement condition survey through a) Manual Method and b) Drone Method to find the accuracy of our model. Classification of road defects are taken according to IRC:82-2015 code for Rural roads (Proforma-1). Table 1 presents the road surface distress measurement results. Figure 2 visualises the difference between both methods.

Name of the road: Valavanthankottai – Thirunedungulam Road; Road length: 4 km; Study Chainage length: 0 to 1.5 km; Type of road: Bituminous Road; Details: It is a single-lane carriageway that connects the villages Valavanthankottai and Thirunedungulam in Trichy district, Tamil Nadu, India. Serves as an important transportation link between the two villages, carrying a significant amount of traffic.

Table 1: Road Surface Distress Measurement

Defects	Manual Method (%)	Drone Method (%)	Difference (%)	Percentage Difference (%)
Cracking	0.99	1.08	0.09	9.09
Ravelling	0.18	0.19	0.01	5.56
Potholes	0.56	0.56	0.0	0.0
Shoving	0.3	0.32	0.02	6.67
Patching	0	0	0	0.0

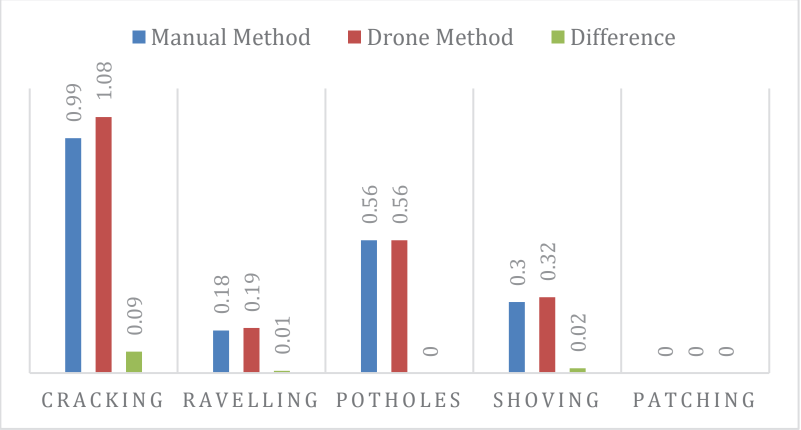

Figure 2: Comparison Chart of Road Surface Distress Measurement by Both Methods

3 Conclusion

This study implemented an intelligent pavement maintenance and management system using drone imagery and artificial intelligence for rural roads. In the present scenario, compared to construction, maintenance is a very difficult task for Indian infrastructure projects. Road system undergoes immense distresses on a frequent basis due traffic, overloading, change in temperature and climate. Thus, frequent monitoring and distress survey is mandatory but conventional manual distress survey and direct visual inspection couldn't keep up with the ever-growing demand and proves inefficient in accuracy. Immediate rectification of distress and damages helps in extending the life of the road infrastructure. Though multiple methods are available including conventional manual survey, they lack accuracy, efficiency, and swiftness. The system implemented by the study deals with accuracy extraordinarily as demonstrated in the case study where accuracy increased by 5.91% overall. Reduction of manual labour with UAV and automated distress identification increased the efficiency of the survey. Time intensive nature of manual survey is solved by fast processing of CNN and enhancement in the structure of corresponding road maintenance organisation. This helps increasing the frequency of monitoring, thereby supplementing immediate response to any distress.

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