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APPLICATIONS OF UNMANNED AERIAL VEHICLES IN PAVEMENT ENGINEERING: RECENT ADVANCES AND CHALLENGES

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Abstract

Unmanned aerial vehicles (UAVs), commonly known as drones, have become a transformative technology in civil and transportation engineering, offering new perspectives for pavement inspection, evaluation and management. Their ability to rapidly capture high resolution imagery and sensor data from multiple perspectives makes them particularly well suited for assessing the condition of extensive road networks. Recent advances have shown that UAVs equipped with optical, thermal, multispectral and LiDAR sensors can efficiently detect surface distresses such as cracks, rutting, potholes and material degradation. Furthermore, photogrammetry and structure from motion techniques enable the development of accurate 3D pavement models, which are increasingly used to evaluate roughness, deformation and drainage performance. Beyond condition assessment, UAVs are being integrated into broader pavement management systems to support data driven decision making, predictive maintenance and the creation of digital twins. Advances in artificial intelligence and computer vision enhance the automatic detection and classification of pavement defects, reducing the need for labour intensive field surveys. These capabilities not only improve operational efficiency and safety but also expand opportunities for long term monitoring and life cycle performance analysis of road infrastructure. Despite these advances, significant challenges remain. Technical issues include limited flight endurance, sensor sensitivity to environmental variability and the lack of standardised data collection protocols. Practical barriers include regulatory restrictions, safety concerns in densely populated environments and the need for integration with established pavement evaluation frameworks. Additionally, there is a pressing need for harmonised methodologies to ensure the reliability and comparability of UAV based assessments across regions and agencies. This paper reviews recent progress in UAV applications in pavement engineering, highlights emerging technologies and discusses key challenges that must be addressed to enable their widespread adoption in the future of pavement management.

Keywords: unmanned aerial vehicles (UAVs), pavement engineering, pavement condition assessment, photogrammetry, LiDAR, digital twin

1 Introduction

Road infrastructure is a fundamental component of modern transportation systems and plays a crucial role in economic development, population mobility and social connectivity. The functionality and safety of road networks depend largely on the condition of pavements, which undergo continuous degradation throughout their service life due to traffic loading,

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environmental conditions and bitumen ageing [1]. Timely detection of damage and reliable pavement condition assessment are therefore essential for effective maintenance planning and optimal management of financial resources. Traditional pavement condition assessment systems, developed over decades, rely primarily on visual inspections, manual field measurements and specialised sensor equipped vehicles [2]. Although these systems have demonstrated high reliability, their use is often associated with high costs, limited spatial and temporal data resolution and the need for traffic closures or speed reductions. Additionally, visual inspections are subject to assessor subjectivity [3], which can lead to variability in pavement condition ratings and hinder long term monitoring of degradation processes.

With increasing demands for traffic safety, infrastructure sustainability and maintenance cost optimisation, there is a growing need to develop new technologies and methodologies that enhance existing approaches. Digital transformation, driven by advances in sensor technologies, data processing and artificial intelligence, has created new opportunities for the collection, analysis and interpretation of pavement condition data [4]. Within this broader technological context, unmanned aerial vehicles (UAVs) have emerged as one of the most promising technologies for modernising pavement inspection and management. Over the past two decades, UAV technology has seen significant advances in autonomous navigation, sensor miniaturisation and increased computational power for data processing. A particular advantage of UAV systems is their ability to rapidly and flexibly acquire high resolution spatial data at relatively low operational costs and with minimal impact on traffic flow [5].

In pavement engineering, UAV technology offers a new perspective on pavement condition assessment by providing spatially detailed data that can be collected more frequently than with traditional methods. By integrating various sensors, including high resolution RGB cameras, thermal, multispectral and LiDAR systems, UAVs enable comprehensive analysis of surface and, to some extent, subsurface characteristics of pavement structures [5, 6]. These data allow for the detection of a wide range of distresses, from surface cracking and rutting to moisture related anomalies and structural degradation [7]. Alongside the development of UAV sensor systems, rapid advances in artificial intelligence and computer vision have enabled the automation of pavement distress detection and classification [8]. Deep learning algorithms, particularly convolutional neural networks, have shown exceptional potential in analysing large volumes of UAV acquired imagery, reducing the need for labour intensive manual analyses and increasing assessment objectivity [9]. This technological progress is a key prerequisite for integrating UAV derived data into pavement management systems and for developing predictive maintenance models. Despite its significant advantages, the application of UAV technology in pavement engineering still faces several technical, regulatory and methodological challenges.

2 Characteristics of UAV technology relevant to pavement engineering

The development of UAVs in recent decades has been characterised by exceptionally rapid technological progress, enabling their transformation from specialised military systems into widely accessible tools for civil and engineering applications. Key drivers of this development include the miniaturisation of electronic components, improvements in the energy efficiency of propulsion systems, advances in autonomous navigation and a significant increase in the computational power of onboard systems [10]. In pavement engineering, these technological advances have facilitated the development of UAV platforms capable of reliably acquiring high resolution data on pavement surface conditions at relatively low operational costs.

In engineering applications, small and medium sized UAV platforms are most used and can be broadly classified, based on their structural characteristics, as multirotor or fixed wing aircraft.

Multirotor UAVs, owing to their ability to take off and land vertically and to hover, are particularly well suited for detailed pavement inspections over limited sections, intersections and urban areas. Their precise positioning capability enables the acquisition of imagery with very high spatial resolution, which is essential for detecting fine scale surface distresses such as early-stage cracking or local material degradation. In contrast, fixed wing UAVs offer significantly longer flight endurance and greater area coverage, making them more suitable for surveying extensive road networks, particularly in rural and sparsely populated regions. Although these platforms have limited hovering capability and require more complex take-off and landing procedures, their superior energy efficiency makes them well suited for regional scale infrastructure inspections.

Regardless of platform type, sensors are a critical component of UAV systems in pavement engineering. The most widely used sensors are high resolution RGB cameras, which enable detailed visual analysis of pavement surfaces and form the basis of most research focused on distress detection. Advances in digital camera technology, including increased pixel counts and reduced image noise, have made it possible to identify very fine pavement surface details even at relatively high flight altitudes [11]. In addition to optical sensors, thermal cameras have attracted increasing attention due to their ability to capture surface temperature distributions. Thermal data have proven particularly useful for identifying anomalies associated with moisture presence, layer delamination and hidden structural defects that are not visible in the optical spectrum [12]. Although the interpretation of thermal imagery is often more complex and strongly dependent on environmental conditions, its integration with RGB data significantly enhances the diagnostic capabilities for pavement structures [13, 14]. Multispectral and hyperspectral sensors represent a further step in the development of UAV technologies for pavement engineering [7, 15]. These sensors enable the acquisition of reflected radiation across multiple spectral bands, allowing the analysis of pavement material properties and the identification of degradation processes related to oxidation, contamination, or changes in binder characteristics. Although such systems are still relatively rare in operational practice, their application demonstrates considerable research potential.

A particularly important direction of development is the integration of LiDAR sensors on UAV platforms [6, 10, 16]. UAVs equipped with LiDAR systems enable direct and highly accurate 3D measurements of pavement surface geometry, largely independent of lighting conditions. Such systems have proven especially valuable in complex urban environments, where shadows, vegetation and variable illumination can significantly affect the quality of optical imagery. Despite their relatively high costs and demanding data processing requirements, UAV LiDAR technologies are increasingly recognised as a key component of future systems for detailed geometric analysis of pavements.

In addition to sensor technologies, flight planning, georeferencing and data processing systems play a crucial role in the application of UAVs in pavement engineering. Precise flight planning, including the selection of flight altitude, speed and image overlap, is essential for ensuring data quality and the reliability of subsequent analyses. Furthermore, the use of advanced global navigation satellite systems (GNSS) and inertial measurement units enables a high level of geometric accuracy, which is a prerequisite for integrating UAV derived data with other information sources within pavement management systems.

Taken together, these characteristics indicate that UAV technology in pavement engineering should not be regarded merely as a replacement for existing inspection methods, but as a foundation for developing new, integrated approaches to data acquisition and analysis. A thorough understanding of the technical capabilities and limitations of different UAV platforms and sensors is therefore essential for effective application in both research and engineering practice.

3 Applications of UAVs in pavement engineering

While early studies primarily demonstrated the feasibility of UAV based pavement inspection, more recent research has increasingly focused on automated, data driven approaches that integrate deep learning techniques, multi sensor data acquisition and broader pavement management concepts [9, 17]. This evolution marks a gradual transition from proof-of-concept investigations to methods designed to support more systematic, repeatable and scalable pavement condition assessment.

Recent developments are particularly evident in automated pavement surface distress detection, where high resolution imagery acquired by UAV platforms is commonly used as input for deep learning models. Convolutional neural networks have been widely applied to the detection and classification of pavement surface distresses, including cracking and surface deterioration, with several studies reporting improved robustness and consistency compared to traditional image processing approaches under controlled conditions [9, 17]. The adoption of data driven methods reduces reliance on manual visual interpretation and enables more efficient processing of large image datasets, which is especially relevant for network level pavement inspections [9, 18].

At the same time, existing research consistently highlights that the performance and generalisation capability of deep learning models are strongly influenced by data quality and acquisition parameters, such as flight altitude, image resolution, illumination conditions and pavement surface characteristics [18, 19]. These findings have led to increased attention to data preparation procedures, annotation strategies and the need for more standardised UAV data acquisition protocols.

In parallel with advances in image-based distress detection, UAV based photogrammetry has been increasingly investigated for the quantitative assessment of pavement surface geometry. By applying structure from motion techniques, overlapping UAV images can be processed into 3D surface models that support the analysis of rutting, local surface deformation and surface texture characteristics [20]. Several studies indicate that UAV derived point clouds can achieve geometric accuracy sufficient for monitoring deformation trends and supporting maintenance prioritisation at the network level, particularly when changes over time are considered rather than absolute measurements [20].

Furthermore, recent research suggests that roughness related indicators derived from UAV based 3D surface models show moderate to strong correlations with conventional roughness metrics when used for relative comparison and condition ranking rather than as direct replacements for standard measurement techniques [5, 7]. These results indicate that UAV photogrammetry can serve as a complementary data source within pavement condition assessment frameworks.

The limitations of purely image-based approaches in shadowed, textured, or visually complex environments have motivated growing interest in UAV mounted LiDAR systems for pavement assessment. UAV LiDAR provides direct 3D measurements that are largely independent of ambient lighting conditions and enable detailed surface reconstruction and terrain modelling [16, 21]. Recent studies further demonstrate that UAV LiDAR data can support the extraction of road surface geometry and longitudinal profiles with accuracy suitable for deformation analysis, although broader operational application remains constrained by sensor costs, payload limitations and the complexity of data processing workflows [6, 16]. As a result, recent research increasingly explores hybrid sensing approaches that combine photogrammetric imagery and UAV LiDAR data to balance spatial resolution, geometric accuracy and operational feasibility [6]. Such data fusion strategies aim to leverage the complementary strengths of each sensing modality while mitigating their individual limitations. Beyond surface geometry, UAV mounted thermal sensors have been investigated for the identification of moisture related damage and subsurface anomalies in pavement structures.

Thermal infrared imaging has been shown to reveal surface temperature patterns associated with moisture accumulation, debonding and subsurface defects [22, 23]. However, the interpretability of thermal data is highly dependent on environmental factors such as solar radiation, ambient temperature and wind conditions. Consequently, UAV based thermographic surveys are generally regarded as supportive diagnostic tools that require careful survey planning and validation against reference measurements [22, 23].

The increasing maturity of UAV based data acquisition has also led to applications in monitoring pavement construction and maintenance activities. Repeated UAV surveys can provide objective documentation of construction progress, geometric conformity and compaction related indicators while minimising disruption to traffic operations [22, 23]. When conducted before and after maintenance or rehabilitation interventions, UAV based surveys support the evaluation of treatment effectiveness and contribute to long term monitoring of pavement performance.

More recently, research has begun to explore the integration of UAV derived data within broader infrastructure management and digital twin concepts. Digital twins provide a framework for integrating spatial information from UAV surveys with condition indicators and analytical models, enabling a more holistic representation of pavement assets and supporting scenario-based analyses of maintenance strategies [24]. Although such approaches are still at an early stage of application in pavement engineering practice, they suggest a potential pathway for more integrated and data driven pavement management systems.

Overall, recent studies indicate that UAV technology has become a versatile and increasingly mature tool within pavement engineering research. Rather than replacing conventional assessment techniques, UAV based methods are best regarded as complementary approaches that enhance data availability, spatial resolution and monitoring flexibility. Further progress in standardisation, validation and integration with existing pavement management frameworks is still necessary to support their wider adoption in engineering practice.

4 Challenges for the implementation of UAVs

Despite rapid technological development and growing interest in the application of UAVs in pavement engineering, their wider and routine use remains limited by a range of technical, regulatory and methodological challenges. These challenges arise not only from the technological limitations of UAV systems themselves, but also from the complexity of integrating a new technology into existing institutional, operational and normative frameworks for road infrastructure management. Technical limitations of UAV systems represent the first and most visible set of challenges. One key issue is limited flight endurance, particularly for multirotor platforms, which are most used for detailed pavement inspections [25, 26]. Limited battery capacity directly affects the maximum length of road section that can be surveyed in a single flight, which may hinder the application of UAV technology across extensive road networks. Although fixed wing UAVs offer significantly longer flight times, their use is often constrained by requirements for take-off and landing space, as well as reduced flexibility in urban environments.

In addition to flight endurance, sensor sensitivity to environmental conditions is a major technical challenge. The quality of RGB and multispectral imagery strongly depends on lighting conditions, the presence of shadows, reflections and meteorological factors, which can lead to variability in data quality and complicate temporal comparability [18, 19]. Thermal cameras are also sensitive to daily temperature fluctuations, wind speed and preceding weather conditions, requiring strictly defined data acquisition protocols to ensure the interpretability of results [27]. Although LiDAR sensors largely eliminate dependence on lighting conditions, their application remains limited by high sensor costs and complex, computationally demanding data processing workflows.

A further technical challenge relates to the management of large volumes of data generated by UAV systems. High resolution imagery and densely sampled LiDAR datasets require substantial computational resources for storage, processing and analysis. In practice, this can pose a serious obstacle for road authorities that lack adequate IT infrastructure or specialised personnel. Furthermore, the time required for data processing, especially for photogrammetric and LiDAR analyses, can limit the ability to respond rapidly in cases of critical pavement distress.

Regulatory challenges constitute another important set of constraints on the application of UAV technology. In most countries, the operation of UAVs is subject to strict regulations governing flight altitude, distance from people and objects, visual line of sight requirements and use in urban and densely populated areas [28]. Such restrictions can significantly hinder the deployment of UAV systems on heavily trafficked roads, where pavement inspections are often most needed. In addition, requirements related to operator licensing, insurance and flight approvals increase administrative burden and the overall cost of UAV implementation. Safety considerations also play a crucial role within the regulatory framework. The potential for technical failures, loss of control, or collisions with vehicles and pedestrians represents a serious risk that must be adequately managed. Public perception of UAVs, often shaped by concerns related to safety and privacy, further influences the acceptance of this technology in practice. These factors highlight the need for the development of clear and balanced regulatory frameworks that ensure safety while enabling technological advancement.

Methodological challenges may represent the most significant obstacle to the long-term integration of UAV technology into pavement engineering. Despite a large body of research [29], there is still no generally accepted set of standardised methodologies for the acquisition, processing and interpretation of UAV data in the context of pavement condition assessment. Differences in flight parameters, sensor types, data resolution and processing methods can lead to substantial discrepancies in results, even when analysing the same pavement section. A particular issue concerns the comparability of UAV based pavement condition indicators with traditional indicators used in pavement management systems, such as the Pavement Condition Index (PCI) or roughness measures. Without a clear link between new UAV derived indicators and existing decision-making criteria, the integration of UAV technology into operational PMS frameworks remains limited. This challenge is further emphasised by the need to validate UAV based methods against established reference techniques, which requires extensive field testing and long-term studies. Moreover, the development of artificial intelligence-based algorithms introduces additional methodological challenges related to transparency, reproducibility and generalisation of results. Machine learning models are often trained on limited datasets, which may reduce their reliability when applied under different conditions, sensors or to other pavement types [26]. Without standardised datasets and clear evaluation criteria, it is difficult to objectively compare the results of different studies and solutions. These challenges indicate that the successful application of UAV technology in pavement engineering requires an interdisciplinary approach that encompasses not only technological development, but also the adaptation of regulatory frameworks, the development of standards and the strengthening of institutional capacities. Addressing technical, regulatory and methodological challenges is a key prerequisite for transitioning UAV technology from the experimental phase to widely accepted engineering practice.

5 Conclusion

The use of UAVs in pavement engineering marks a significant advancement in the modernisation of pavement inspection and management. Recent studies show that UAV technology, combined with advanced sensors and data processing techniques, enables rapid and spatially detailed pavement condition assessment while reducing costs and traffic disruption.

High-resolution optical, thermal, multispectral and LiDAR data, supported by photogrammetry and machine learning, improve the detection of surface distresses, structural anomalies and pavement deformation. Research confirms that UAV-based methods effectively support the identification of cracks, rutting and other deterioration mechanisms, as well as the generation of 3D pavement models for temporal monitoring. The integration of UAV-derived data into pavement management systems and digital twin concepts offers potential for objective, data-driven decision making and predictive maintenance. However, UAV technologies are best regarded as complementary to conventional assessment methods rather than direct replacements.

Despite notable progress, widespread implementation remains constrained by technical, regulatory and methodological challenges. Limited flight endurance, environmental sensitivity of sensors, complex data processing, regulatory restrictions and the lack of standardised methodologies continue to hinder routine application. Overall, UAV technology shows strong potential to become an integral component of future pavement management frameworks; however, its successful adoption will require further standardisation, long term validation and closer integration with existing engineering and regulatory practices.

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