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EVALUATION OF THE USE OF UAVS IN FLEXIBLE PAVEMENT INSPECTION BY USING GCPS: A CASE STUDY ON PALESTINIAN ROAD

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Master's Thesis

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İstanbul, 2025

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I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Ismail S A ABURQAQ

Signature

DEDICATION

To those who have always believed in us …

To those who have been our source of inspiration …

To those who gave us strength …

To those who provide us with their endless support and encouragement …

To our families …

To our friends…

To everyone who carries love in his heart for us...

PREFACE

It has been a great opportunity for us to gain a lot of knowledge through working on this thesis, but the successful completion of any task would be incomplete without mention of the people who made it possible. For that, we would like to thank everyone who helped, supported, and encouraged us: Altinbaş University, Engineering College, and Civil Engineering Department, including all members of the helpful and reverent staff. Special thanks to our supervisors, Prof. Dr. Sepanta Naimi and Asst. Prof. Dr. Sepehr Saedi was the guiding light as we worked on this thesis. also, many thanks to Mr. Musab Shaheen, who played a role in the success of the research idea Mr. Musab Shahin. Thanks to all the instructors for all their efforts to provide us with all the useful information and for sharing their knowledge and experience to make us successful engineers. Finally, our deep gratitude and sincere thanks to our parents, brothers, and sisters for their patience, to everyone who tried to help us during our work and gave us the strength to complete this task.

ABSTRACT

EVALUATION OF THE USE OF DRONES IN FLEXIBLE PAVEMENT INSPECTION BY USING GCPS: A CASE STUDY ON URBAN ROADS IN PALESTINE

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Since rehabilitation plans are developed based on the results of pavement condition assessments, It's a crucial component of contemporary pavement management systems. These methods create challenges for road maintenance and repair programs due to seasonal limitations, low accuracy, visual errors, time consumption, and high costs. Existing pavements need to be properly evaluated, and this requires ongoing, efficient monitoring using acceptable tools in all weather and traffic conditions. unmanned aerial vehicles (UAVs) offer a novel and intriguing option for a wide range of activities, including dam monitoring, road Inspection, and building 3D ground models and orthophoto, due to their high level of accessibility, low cost, and safety. This research aims to use the mentioned technology to assess the severity and type of asphalt damage. To achieve the research objectives, ground control points were used in the image processing of vertical photogrammetric mapping to reconstruct 3D road models, which were processed and analyzed using the Agisoft Photoscan software. through the Agisoft Photoscan software tool, the patch area, rut depth, and crack type located on the road pavement were detected and their dimensions were extracted. Compared to field surveys, the results of the detection provide high accuracy with an error of about ± 3 mm in the rut's depth, ± 2.44 cm^2 in the patches and potholes areas, and an accuracy of up to 96% in identifying cracked areas and the type of cracks in most cases. In conclusion, this study demonstrated the ability of ground control points to enhance the accuracy of the image of a drone for road distress extraction, especially in conditions where photographing is difficult from a low altitude and in critical weather and traffic conditions.

Keywords: Flexible Pavement, Assessment, Ground Control Points (GCPs), Accuracy, Inspections, UAVs, Asphalt Pavement.

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ABBREVIATIONS

3D	:	3 Dimensions
DEM	:	Digital Elevation Model
FWD	:	Falling Weight Deflectometer
GCP	:	Ground Control Point
GCP	:	Ground Control Point
GPR	:	Ground Penetrating Radar
GPS	:	Global Positioning System
LiDAR	:	Light Detection and Ranging
NDT	:	Non-Destructive Testing
RMSE	:	Root Mean Square Error
RTK	:	Real-Time Kinematik
UAV	:	Unmanned Aerial Vehicle

1. INTRODUCTION

1.1 GENERAL OVERVIEW

The great majority of countries transport goods and passengers utilizing the highways. The wear and tear that is caused by traffic, the passage of time, and the weather will eventually lead to the deterioration of roads, just as it does with every other kind of transportation infrastructure[1]. The organizations that are responsible for managing roads dedicate a significant amount of time and resources to the examination of the state of the pavement surfaces[2]. They do this as part of their efforts for asset management so that they can confirm that the roads are in a serviceable condition. The information that is relevant to the condition of the pavement surface. serves as a guide for the decisions that these organizations make about maintenance and repair[3]. Pavement evaluation was conducted using a technique known as the "pavement evaluation method" in previous times. The number of people who are killed or injured in roadway events every year is unacceptably high, which makes highway safety one of the most urgent concerns that the world is now facing. The most crucial component of the land transportation infrastructure is made up of flexible pavements. The numbers two, four, and five. The advancement of a nation's transportation infrastructure, which includes the building of roadways, is advantageous to its economy. The reason for this is that it brings about economic and societal advantages [5,6]. Considering into account both the professionals' ocular assessments of the situations and their subjective evaluations of the conditions on the surface, Inspectors went into the field and documented the condition of the pavement surface by hand in order to get the necessary information to construct a database on a computer. The automated pavement surface inspection system is equipped with digital, laser, and high-resolution vehicle-mounted video sensors, which allows it to identify potential problems. The fact that the observations themselves are carried out on the ground necessitates that both the human and automated observation methods be carried out on the ground as well. The methods that are mentioned above require a significant amount of time to be completed, and they provide a hazard to those who are responsible for inspecting highways. This is due to the fact that they are impacted by the thoughts that people have, they involve a considerable amount of effort, and they are costly. In addition to this, they necessitate the support of specialists, and they have the capacity to result in inaccuracies in spatial and assessment data [7, 8]. The most favorable conditions for service along the routes are provided by the strategy of maintaining pavement, which is also designed to minimize the effect on the regularity of traffic on the roads during their operation [9,10]. Unmanned aerial vehicles (UAVs) that are being operated on platforms have become an increasingly important source of information for contemporary issues that are related to the following three areas: three-dimensional modeling, pavement inspection, and map generation [11,12,13]. The creation of three-dimensional models from pictures that have been obtained by unmanned aerial vehicles (UAVs) is easily available at this time [4, 9, 12]. The development of a detailed, realistic model may provide accurate information on the state of the road, which might be beneficial in the process of keeping track of the health of the pavement and the safety of the road. As a result of this, engineers and maintenance personnel will be able to gain a better knowledge of the condition of the pavement. This will enable them to spot any potential issues at an early stage and to implement the necessary maintenance and repair processes in order to ensure the safety of the road [14,15].

The primary goal of pavement maintenance is to keep service conditions intact while minimizing any disruptions to the flow of traffic [9,16]. In the past several years, Unmanned Aerial Vehicles (UAVs) have proven to be extremely useful instruments for the purposes of three-dimensional modeling, mapping, and pavement inspection. These vehicles provide new potential to improve the efficiency and accuracy of pavement management [11-13]. By processing the footage that has been collected by unmanned aerial vehicles (UAVs), it is possible to build three-dimensional models that are extremely accurate and lifelike. These models provide engineers with a thorough understanding of the state of the pavement. The timely identification of distress and the facilitation of prompt repair measures are made possible by these models. Both the safety and the lifetime of road infrastructure are improved as a result [4,14,17].

Unmanned aerial vehicle (UAV) inspections provide substantial environmental benefits in addition to operational and technological advantages. Unmanned aerial vehicles (UAVs) have a role in the reduction of greenhouse gas emissions and the minimization of carbon footprints. They do this by decreasing the reliance on vehicles that are powered by fuel and by limiting disturbances to traffic. As a result, they are in accordance with worldwide sustainability objectives and with urban planning techniques that take into consideration the environment. According to research that has been conducted, the use of unmanned aerial vehicle (UAV) inspections has the potential to cut carbon emissions by as much as ninety percent when compared to traditional inspection techniques that utilize vehicles [18-20]. As a result, the incorporation of unmanned aerial vehicle technology into pavement management systems not only enhances the overall technical performance and operational efficiency of these systems but also demonstrates a commitment to environmental responsibility. This incorporation, therefore, serves as evidence of the strong synergy that exists between contemporary infrastructure management practices and sustainability goals [21].

Not only does the unmanned aerial vehicle inspection approach improve the accuracy and efficiency of pavement assessments, but it also plays a critical role in the promotion of sustainable pavement maintenance. Unmanned aerial vehicles are capable of facilitating targeted rehabilitation by accurately pinpointing locations that have been damaged or have degraded. This approach minimizes the number of superfluous interventions that are required and optimizes the distribution of resources. The development of Reclaimed Asphalt Pavement (RAP), which may then be recycled utilizing plant-mixed cold recycling procedures in combination with emulsified asphalt, is frequently the result of this method [22].

The quality and efficacy of pavement materials that have been recycled are heavily influenced by the state and properties of the initial asphalt and aggregate components. This underscores the crucial significance of conducting an accurate and in-depth study of the pavement prior to the recycling process. (UAV)-Based approaches contribute to the extension of the service life of pavements, the reduction of material waste, and the promotion of environmentally responsible infrastructure management practices by making use of the combination of precise inspection and the sustainable reuse of materials [23].

The significance of decreasing both material usage and carbon emissions has been highlighted by recent advancements in the building industry. These advancements correspond with the aims of sustainability that have been established on a worldwide scale. Within this context, Amro and Naimi developed and presented a novel framework known as Symmetry Optimization and Detection for Architecture (SODA), which incorporates continuous symmetry measurement (CSM), computer vision, and evolutionary algorithms in order to enhance the structural symmetry of buildings [24].

The framework was applied to fifty structures located in the Netherlands, which covered an area of over 2.287 million square meters, and the results showed that it was able to make considerable improvements to the efficiency of the structures. As a result of an improvement in the average symmetry score from 68.4 percent to 82.7 percent, there was an 18.5 percent reduction in material use, a decrease in construction time of 19.2 percent, and cost savings of about €87.3 million, as well as a reduction in carbon dioxide emissions of 21,450 tons. The findings that have been made demonstrate that the optimization of performance based on symmetry has the ability to improve both environmental and economic outcomes, while at the same time ensuring that structural safety and regulatory compliance are maintained [24].

Contemporary urban infrastructure necessitates efficient and sustainable transportation systems that blend technological advancement with financial feasibility. Vardar, Altan, and Naimi assert that it is crucial to assess both economic and technological elements to optimize transportation performance and reduce operating costs. Their research highlights the possibility for employing innovative solutions in transportation system planning to enhance efficiency, augment safety, and mitigate environmental impacts. It also offers a framework applicable to urban road networks and facilitates the incorporation of advanced inspection technology, such as unmanned aerial vehicles [25].

The factors of structural resilience and durability are of utmost importance in the field of civil engineering, especially in areas that are prone to earthquakes. According to Naimi and colleagues (2013), it was found that the inclusion of multilongitudinal gaps in the beam web was one of the strategies that might be utilized in order to increase the ductility of post-Northridge beam-to-column connections. The results of their research provide evidence that the implementation of structural alterations of this kind has the potential to considerably enhance the ability to dissipate energy and deformability without reducing the capacity to bear loads. This conclusion underscores the need of implementing novel engineering solutions in order to guarantee the safety of infrastructure and its ability to function over the long term [26].

In order to reduce expenses and the effects on the environment while also ensuring quality, it is becoming more and more essential to implement sustainable techniques in the building of roads. The authors Reihanifar and Naimi (2018) underline the importance of utilizing Value Engineering (VE) as a systematic technique to analyze road building projects, which may help discover potential for efficiency improvements and resource optimization. It is shown by their study that the implementation of VE may increase the sustainability of a project by minimizing expenditures that are not essential, by optimizing the amount of materials that are used, and by increasing the overall performance of the project. As a result, it is a viable tool for strategies of inspection and management of urban roads that are contemporary [27].

Maintaining the condition of roads and prolonging the lifespan of infrastructure requires effective pavement management systems (PMS). In the course of their investigation of the implementation of PMS in Afghanistan, Naimi and Karimi (2019) brought attention to the significance of systematic monitoring, maintenance priority, and the allocation of resources in the enhancement of pavement performance. The significance of incorporating state-of-the-art inspection technology as well as decision-making processes that are based on data in order to improve the sustainability and efficiency of road networks is emphasized by their results [28].

The use of project management strategies is critical in order to guarantee that construction projects are completed on time, within budget, and to the highest possible standard. The study conducted by Akbay and Naimi (2021) investigated the application of these approaches in the building of the Aksaray Mahmudiye Secondary School. The results of this investigation provided evidence that structured planning, scheduling, and monitoring contribute to a considerable increase in the efficiency of projects as well as the exploitation of resources. The research that they have conducted emphasizes the advantages of incorporating systematic management techniques into building projects. This integration can also be beneficial in the support of inventive inspection methods, such as assessments of pavement that are conducted using drones [29].

1.2 PROBLEM STATEMENT

The integration of Unmanned Aerial Vehicles (UAVs) into flexible pavement assessment methods is a field that has not yet been adequately investigated. Although it has already been proven that drones are of great value in a number of different construction and infrastructure monitoring applications, their ability to specifically identify pavement distress, evaluate surface conditions, and lower the costs of operations in flexible pavements has not yet been fully examined. As a result, there are still unanswered problems about the practical application, dependability, and capacity of unmanned aerial vehicle (UAV) inspection techniques when it comes to flexible pavement networks. The purpose of this research is to conduct a systematic assessment of the practicality, benefits, and possible drawbacks of utilizing drones for the purpose of inspecting flexible pavement. The investigation will concentrate specifically on the drones' capacity to capture high-resolution images, accurately detect surface defects, and provide more affordable alternatives when compared to conventional inspection methods. The purpose of this research is to gain insights into how unmanned aerial vehicle (UAV) technology may be used to enhance pavement assessment methods, reduce the dangers that are inherent in human inspection activities, and make the most effective use of resources when it comes to the efficient maintenance and management of infrastructure assets.

1.3 PURPOSE OF THE THESIS

The overarching objective of this thesis is to provide a thorough assessment of the utilization of drone technology in the examination of flexible pavements, with a specific emphasis on its capacity to effectively detect distress in pavements and improve the precision of the data that has been gathered. Ground Control Points (GCPs) are an essential component of this evaluation, and they serve a crucial function in enhancing the precision of the three-dimensional models that are produced from unmanned aerial vehicle (UAV) footage. In addition, they are responsible for guaranteeing the dependability and quality of the data that has been collected. This emphasis is particularly pertinent when taking into consideration the growing need for regular and in-depth inspections of the pavement in areas that are highly urbanized. In these regions, effective monitoring is a critical component in the maintenance of the quality of infrastructure. The purpose of this study is to conduct a systematic evaluation of the practicality, advantages, and constraints associated with the use of unmanned aerial vehicle (UAV)-based inspection methods, as well as to compare the performance of these methods to that of traditional inspection techniques. The major objective of this research is to give practical insights into how drone technology might be used to contribute to more effective, accurate, and resource-efficient pavement repair tactics.

1.4 AIMS AND OBJECTIVES

The aim of this thesis is to perform an extensive evaluation of the effectiveness of Unmanned Aerial Vehicle (UAV) technology in the inspection of flexible pavements, with an emphasis on its capacity to detect pavement distress with accuracy, increase inspection efficiency, and enhance the overall quality of the data that is gathered. The goal of the study is to conduct a systematic comparison between the performance of drone-based inspections and that of traditional techniques in terms of their accuracy, efficiency, and cost-effectiveness. Furthermore, it aims to assess the constraints and obstacles that are connected with the integration of unmanned aerial vehicle (UAV) technology into regular pavement inspection processes, while also investigating its ability to detect a variety of surface distresses that could otherwise go unnoticed when utilizing human methods. Utilizing Ground Control Points (GCPs) in order to improve the precision of three-dimensional models that are produced from unmanned aerial vehicle (UAV) pictures is an essential aspect of the research. The objective is to guarantee dependable and correct data for decision-making purposes. In conclusion, the research seeks to offer practical advice for enhancing the efficiency and application of drones in pavement maintenance plans, which will contribute to enhanced resource allocation, decreased operational risks, and infrastructure management that is based on more informed decisions.

1.5 SCOPE AND LIMITATIONS

This thesis examines the effect that Ground Control Points (GCPs) have on the correctness of three-dimensional models that are produced using data that is acquired by unmanned aerial vehicles (UAVs). The focus of this thesis is on the context of flexible pavement inspections. Although the objective of the study is to give complete insights on the utilization of drones for pavement monitoring, it is susceptible to various limitations. The primary emphasis of this investigation is limited to the examination of sections of flexible pavements. This is due to the fact that flexible pavements are the most prevalent form of pavement. In addition to this, the method of collecting data is limited to only one research area, which is comprised of a certain section of the road network. Due to the fact that this selected stretch of pavement comprises a significant diversity and amount of distress mechanisms, it was chosen as the section of pavement to be assessed for the purpose of evaluating the capabilities of unmanned aerial vehicles (UAVs) to identify different forms of pavement deterioration. The established limitations and constraints guarantee that the research remains focused on its objectives while producing useful and applicable data for evaluating the role of GCPs and UAV technology in pavement inspection methods.

1.6 THESIS LAYOUT

Chapter 1: Introduction This chapter includes the general overview of the thesis, problem statement, purpose of the thesis, aims and objectives, scope and limitations and the thesis layout.

Chapter 2: Literature review. This chapter focuses on the broader research on types of pavements, pavement damage, methods of inspection of heritage damage from traditional to modern techniques, using UAVs for flexible pavement inspection and related works.

Chapter 3: Methodology. This chapter will outline the systematic approach used to evaluate the effectiveness of drone technology in flexible pavement inspection using Ground Control Points (GCPs). It will begin with a description of the study area, followed by detailed information on the UAV system, flight planning, and GCP deployment. Data collection procedures, including image acquisition and pavement distress identification, will be presented. The chapter will also explain the image processing techniques, accuracy assessment methods, and the comparison between GCP-assisted and non-GCP drone data. Finally, the methodology will address potential limitations and legal or ethical considerations relevant to UAV usage in urban environments.

Chapter 4: Results and Discussion, The Results and Discussion chapter will present and interpret the findings obtained from drone-based pavement inspections using Ground Control Points (GCPs). It will begin by showcasing the orthomosaic maps, 3D models, and extracted pavement distress features. Quantitative results such as positional accuracy, surface irregularities, and types of detected distresses will be compared between GCP-enhanced and non-GCP datasets. The chapter will also include an analysis of the efficiency, accuracy, and reliability of the UAV method in the context of urban roads in Palestine. These findings will be discussed in relation to existing literature, highlighting both the advantages and limitations of the approach, and emphasizing the practical implications for road maintenance and infrastructure management.

Chapter 5: Conclusions and Recommendations. This chapter will conclude the thesis and provide recommendations for future work.

2. LITERATURE REVIEW

In this chapter, many researchers have studied this topic, some of whom

are presented as follows:

2.1 OVERVIEW OF FLEXIBLE PAVEMENTS

2.1.1 Pavement Types

There are four essential goals that need to be accomplished during the building of roads and pavements in order to guarantee that they will last for a long time and work well. The objectives encompass the provision of a riding surface that is sufficiently smooth for the use of vehicles, the provision of waterproofing to protect the underlying layers, the provision of suitable protection to the subgrade, and the provision of sufficient skid resistance for safety. The word "pavement" is a wide phrase that may be used to describe any surface that has been developed for the purpose of being used by vehicles or pedestrians. In general, there are three primary categories of pavements: unpaved, stiff, and flexible [30].

In contrast to paved roads, which are roads that have been surfaced with materials in order to enhance ride quality and provide waterproofing, unpaved roads are roads that are primarily composed of gravel surfaces. Depending on the materials that make up the surface layers as well as the structural behavior of those layers, paved roads can be further subdivided into the categories of rigid pavements or flexible pavements. The top layer of rigid pavements, such as concrete, is known for its great stiffness, which is relied upon to disperse loads over supporting layers that are not as strong. Despite the fact that rigid pavements provide a great deal of structural strength, they are not as frequently utilized because of the difficulties that are related with their maintenance and repair [30].

On the other hand, flexible pavements are constructed in such a way that they are able to bend and spread out loads that are applied to them over a number of layers that are underneath them without experiencing any cracks. A succession of layers that make up the base and sub-base are positioned underneath them, with one or more bituminous surface layers being deposited on top of these layers [31].

When it comes to the building of flexible pavements, the process consists of layering materials that have different degrees of stiffness. The materials with the greater degree of rigidity are placed in the top layers, whilst the materials with the higher degree of flexibility are positioned at the bottom. This gradation facilitates the effective distribution of loads and enables the pavement to absorb the bending that is created by tension that results from axle loads of vehicles. The typical surface course of flexible pavements is comprised of a layer of waterproof bituminous material, which serves to safeguard the materials beneath it while also providing a vehicle with a smooth surface to travel on. A common flexible pavement construction is shown in Figure 2.1. This figure demonstrates the layered configuration and functional organization of the materials that are located inside the pavement system [31].

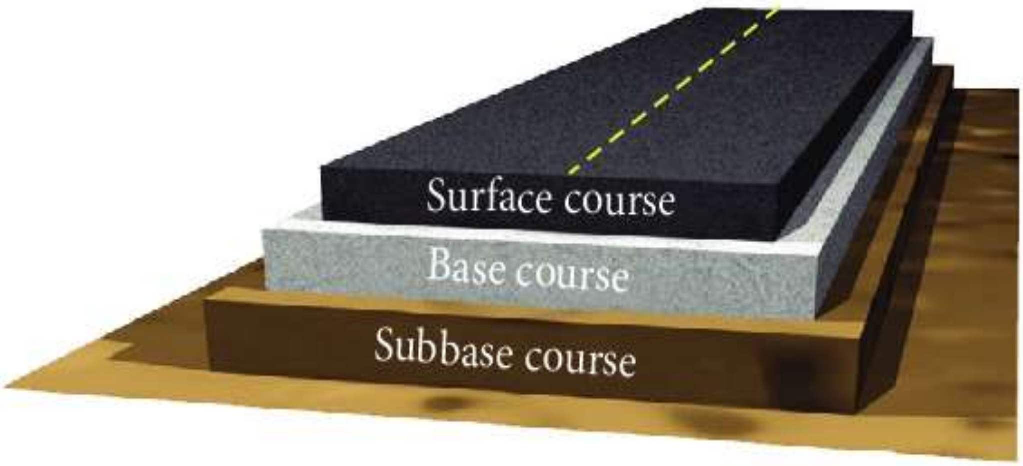


Figure 2.1: Flexible Pavement Structure [15].

2.1.2 Flexible Pavement Distress

In terms of flexible pavements, a number of stressful factors can have an impact on their performance and their long-term durability. These elements include environmental conditions, loads from traffic, deterioration of materials, and aging. Cracking is one of the most common types of pavement distress. It can be caused by a number of factors, including the natural aging of the pavement, repetitive vehicular traffic, thermal expansion and contraction, and structural fatigue. The phenomenon of cracking may occur in a number of different patterns. Some of these patterns include longitudinal, transverse, block, and edge cracking, in addition to alligator cracking (which is also known as fatigue cracking) [32, 33].

Rutting, which is often brought on by the weight of large traffic loads and results in the creation of depressions along tire tracks, is another key discomfort mechanism. The presence of ruts can create a number of problems, particularly when the road is wet, because of the lower resistance to skidding and the possibility of hydroplaning . The presence of fractures and ruts on the surface of the pavement enables water to infiltrate the pavement's structure, which in turn hastens the degradation of the components that make up the foundation. The development of potholes, which further undermines the safety and performance of pavement, is a frequent consequence of this process. When it comes to the evaluation of unmanned aerial vehicle (UAV)-based inspection technologies, it is of utmost importance to have a thorough understanding of these distress mechanisms in order to successfully monitor and maintain pavements[32,33].

Additional kinds of distress in flexible pavements occur from diverse mechanical, environmental, and material-related issues, each of which affects the safety and performance of the pavement. Shoving or pushing is a phenomenon that occurs when high traffic or insufficient compaction causes the lateral displacement of materials on the surface. In the same way, aggregate polishing decreases surface friction, which leads to the creation of slippery situations that put the safety of vehicles at risk. Binder bleeding, which occurs when excessive asphalt binder rises to the top and creates a glossy or sticky coating, can also result in a roadway that is slippery [1,34].

Raveling is yet another distress mechanism that is frequently encountered. The defining characteristic of this phenomenon is the progressive disappearance of aggregate particles from the surface of the pavement. This phenomenon is typically caused by weathering or insufficient compaction, and it is responsible for the development of an uneven texture that makes for a difficult ride. Crack sealing failures happen when the previously applied sealants degrade, resulting in the reappearance of cracks. Thermal cracking occurs as a consequence of changes in temperature, whereas fatigue cracking, which is often seen as linked cracks, develops as a result of the pressures caused by repetitive traffic. The cracks that are seen in asphalt layers can be attributed to either thermal or fatigue cracking [34].

Stripping is a kind of distress that affects pavements in a substantial way. It is brought about by moisture seeping between the layers of the pavement, which results in the asphalt binder losing its adherence to the aggregates and, as a consequence, the pavement's structural integrity is diminished. Because there is such a broad range of distress types and because the complexity of these kinds might vary, it is important to do routine inspections in order to identify any problems as early as possible and to put into practice suitable maintenance or repair procedures that are customized to address each individual type of distress. The process of maintaining ongoing surveillance guarantees that flexible pavements will remain in good condition for an extended period of time and that they will be safe to use. Additionally, it makes it easier to make decisions that are based on reliable information when it comes to maintenance and repair interventions [1].

If these distresses are not dealt with and fixed in a timely way, the service life of the pavement may be substantially reduced, which frequently results in the necessity of expensive repairs or complete resurfacing. Because the consequences of the degradation of pavement accumulate over time, it is essential that maintenance be performed in a timely and preventative manner in order to reduce the amount of additional damage that occurs. A number of instances of flexible pavement distress are shown in Figure 2.2, which also highlights the many ways in which these problems present themselves. states that in order to preserve the structural integrity, operational safety, and cost-effectiveness of pavement maintenance over the long run, it is necessary to properly identify and address certain types of distress [35].

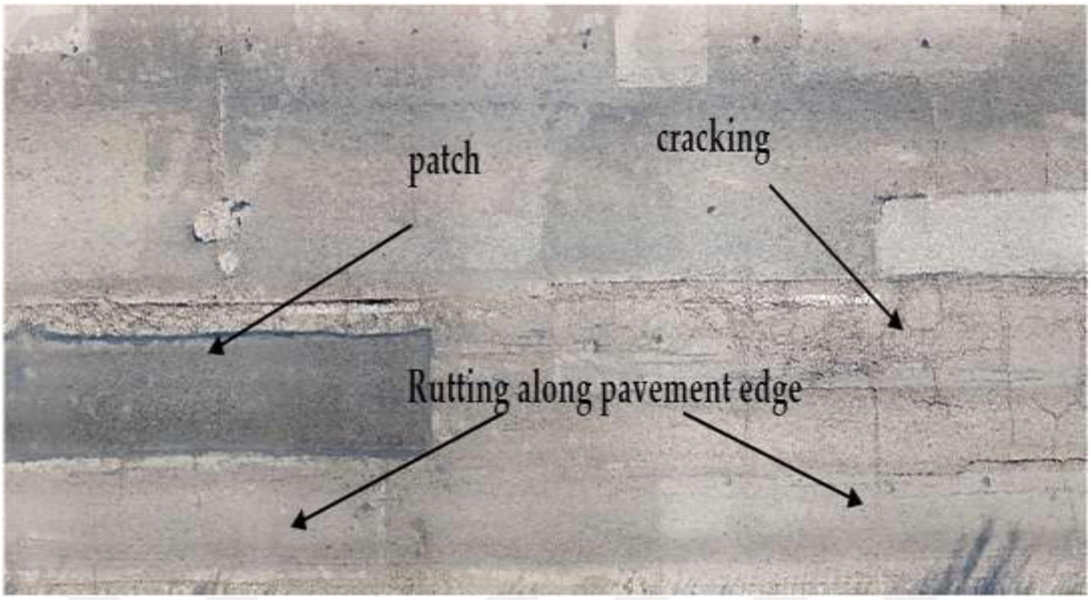


Figure 2.2: Samples of Flexible Pavement Distress [2].

2.2 LITERATURE REVIEW ON METHODS OF FLEXIBLE PAVEMENT INSPECTION: FROM TRADITIONAL TO MODERN TECHNIQUES

2.2.1 Traditional Methods of Flexible Pavement Inspection

In the past, the most common methodologies that were utilized in order to determine the state of flexible pavements were based on physical inspections. These inspections included both visual and manual exams. Among these, eye examination is still the most extensively used and essential approach for judging pavement quality. Inspectors who have received specialized training visually evaluate the surface of the pavement in order to detect any obvious damage, which may include ruts, potholes, cracks, and surface wear [36].

Visual inspections are often thought to be both cost-effective and uncomplicated, but they are also fundamentally subjective. Because of this, they might not be able to uncover subtle or early-stage problems that are not immediately obvious. The variety that is shown in the outcomes of assessments may also be attributed to the amount of experience and training that the inspector has had, since these factors have a significant impact on the accuracy and dependability of visual evaluations [37,38]. In spite of these limitations, visual examination continues to function as a basic technique in pavement condition evaluation due to its simplicity and minimum equipment needs. Nonetheless, the method's dependence on human judgment demonstrates the necessity of utilizing other methodologies that might improve the objectivity, accuracy, and effectiveness of pavement evaluation[38].

distresses are meticulously documented to provide a comprehensive and accurate representation of the pavement condition and to track the progression of defects over time. For example, conducting a visual inspection of a single road lane with a length of approximately 100 meters typically requires only the completion of a standardized inspection form. The magnitude of each distress is measured, often in terms of the length or area affected, and categorized according to severity into three main levels: mild, medium, and severe [39].

In addition to documenting the existing distresses, the same inspection forms are used to record any minor maintenance or repair activities, such as patching, surface treatments, crack sealing, and other similar interventions. When multiple severity levels are present within a single region and cannot be distinctly separated, the highest applicable severity rating is assigned to that region to ensure that the most critical conditions are captured accurately. This systematic documentation is essential for understanding the progression of pavement distress and provides a foundation for planning maintenance, allocating resources efficiently, and informing long-term pavement management strategies [40].

2.2.2 Non-Destructive Testing (NDT) Methods

There exists an increasing trend towards the utilization of non-destructive testing (NDT) technologies in the evaluation of pavements, which has been spurred by the acknowledgement of the inherent limits of traditional pavement inspection approaches. No harm will be done to the surface or to any of the layers underneath it as a result of the evaluation of the pavement's state that is made possible by these methods. Ground Penetrating Radar (GPR) is one of the non-destructive testing (NDT) techniques that is used most frequently. By propagating electromagnetic waves through the pavement layers, GPR is able to provide specific information on the thickness and quality of each layer [41].

Decisions about pavement maintenance and rehabilitation that are based on informed considerations may be made with the use of the data that is acquired from ground penetrating radar (GPR). This eliminates the need for excavation and reduces the amount of disturbance to traffic. In addition to this, ground-penetrating radar (GPR) provides a means of gaining insights into the subsurface properties, such as the amount of moisture present and the structural integrity of the pavement system. These characteristics are of paramount importance for gaining a deeper knowledge of the overall performance of the pavement system [41]. In circumstances when conventional techniques for inspection are impractical or even impossible to put into practice, this technology has demonstrated its worth. Examples of such scenarios include those that take place in places that are difficult to reach or where operating restrictions might potentially hinder the use of typical testing procedures. Ground-penetrating radar (GPR) is a major innovation in the field of pavement condition evaluation as it is able to provide subsurface data with a high resolution without inflicting any harm[42].

In addition to the non-destructive testing method that was mentioned before, the Falling Weight Deflectometer (FWD) is another approach that is often used. With the assistance of this program, which provides data in real time on the deflections of the pavement, it is Aside from the usage of Ground Penetrating Radar (GPR), the Falling Weight Deflectometer (FWD) is another often utilized method of non-destructive testing (NDT) that may be employed in order to assess flexible pavements. The pavement surface is subjected to a load that is being controlled by the FWD device, and the deflections that occur from this stress are measured in real time. The information that is provided by these measures of deflection is crucial for determining the structural integrity and load-bearing capability of the pavement layers. When engineers are making decisions regarding pavement maintenance, rehabilitation, or restoration, FWD evaluations are particularly important since they enable engineers to calculate the pavement's remaining structural life.

When compared to conventional inspection techniques, non-destructive testing (NDT) technologies, such as ground-penetrating radar (GPR) and forward-wave detection (FWD), provide substantial benefits overall. Because they have the ability to quickly and effectively scan broad areas without causing any interruption to traffic, they are considered to be extremely appropriate for thorough pavement condition inspections. Non-destructive testing (NDT) technologies offer a dependable and efficient methodology for the maintenance and management of flexible pavements on a wide scale by utilizing precise structural data in conjunction with little operational impact [43].

2.2.3 Automated Pavement Condition Surveys

As a result, the field of pavement inspection has undergone a significant transformation, moving toward the use of evaluation methodologies that are more objective and efficient. This transition is demonstrated via the creation of automated pavement condition surveys. When traveling over the surface of the pavement, these sophisticated systems usually employ automobiles that are outfitted with accelerometers, high-resolution cameras, and laser scanners to gather detailed information [44]. The acquisition of information that is both comprehensive and accurate concerning the state of the pavement is the fundamental objective of these technologies. After the gathering of data, the subsequent stage is the analysis of the data, which consists of the identification and categorization of a variety of pavement distresses, such as rutting, cracking, and surface roughness [45].

Automated inspection methods provide a more reliable, repeatable, and objective evaluation of pavement conditions than traditional eye inspections. As a result of this increased uniformity, the likelihood of human mistake and the possibility of subjective judgment are diminished, which in turn enhances the reliability and accuracy of the inspection process. Transportation authorities and engineers are able to conduct pavement assessments on a larger scale with more efficiency via the use of these automated procedures, all the while maintaining the integrity of the data that has been gathered by ensuring that it is both comprehensive and reliable [46].

The capacity to carry out surveys at fast speeds and over extended distances is one of the most noteworthy benefits of automated pavement inspection systems, as it significantly increases the efficiency of operations. For example, it is possible for certain automated systems to cover many kilometers of roadway in a few hours, delivering complete and thorough data without depending on substantial manual work. Not only does this capacity result in increased productivity, but it also guarantees a more comprehensive evaluation of the state of pavements over extensive networks [47].

Additionally, it is possible for automated inspections to discover pavement distresses at a more preliminary level, which allows for more accurate predictions of upcoming maintenance and rehabilitation needs. The early diagnosis of problems is especially beneficial for a number of reasons, including the optimization of resource allocation, the reduction of long-term maintenance costs, and the prevention of small distresses from developing into significant structural failures [48].

Having said that, there are a number of obstacles that still need to be overcome before automated inspection technologies may be implemented on a larger scale. Included among these are the significant initial investment required for the equipment and the need for specialized software and skills in order to effectively process and interpret the data that has been gathered. Overcoming these obstacles is critical in order to ensure that automated technologies are fully integrated into contemporary pavement management methods and that the full extent of their potential advantages is realized[46].

2.2.4 Use of Drones and UAVs in Pavement Inspection

Unmanned Aerial Vehicles, which are sometimes referred to as drones, have garnered considerable interest as a cutting-edge method for the evaluation of flexible pavements during the past few years. Unmanned aerial vehicles (UAVs) that are outfitted with sophisticated sensors and high-resolution cameras have been demonstrated to be significantly more effective than traditional techniques for conducting visual inspections across wide regions, such as huge road networks or distant pavement portions, in which conventional inspection methods may be inefficient or unfeasible [49].

The capacity to access places that are difficult to reach is one of the most significant advantages of inspections that are conducted with the assistance of unmanned aerial vehicles (UAVs). This capability makes it possible to provide full coverage of regions that would otherwise prove challenging to monitor [49]. Unmanned aerial vehicles (UAVs) can help to improve safety during inspections, especially in dangerous settings or regions with a lot of traffic, because they eliminate the need for workers to be physically present on the pavement. In addition to this, the deployment of drones minimizes or even eliminates the need for lane closures, which decreases the interruption to traffic and makes them a realistic and efficient choice for highways that are in constant use. Unmanned Aerial Vehicles are becoming more and more appealing as a method for modern pavement management due to the fact that they provide precise, safe, and efficient data collection for infrastructure networks that are large in scale and have a high volume of traffic [50].

Unmanned Aerial Vehicles are being used more and more to gather video data and thermal imaging in addition to doing visual inspections. This information may be examined in order to determine whether or not pavement distress is present. By utilizing machine learning methods and techniques for image processing that are based on artificial intelligence (AI), it is possible to process these photos in order to automate the process of identifying and classifying a wide range of pavement distresses. The use of artificial intelligence in unmanned aerial vehicle inspection systems has resulted in a considerable improvement in their precision, effectiveness, and capacity to analyze big amounts of information [49].

Despite the fact that significant breakthroughs have been made, there are still a number of problems that need to be overcome in order to successfully employ unmanned aerial vehicle-based pavement inspections. The operation of unmanned aerial vehicles is highly dependent on the weather, which restricts their use when conditions are unfavorable. Furthermore, the length of time that drones are able to stay in the air is limited, which may limit the amount of ground that can be covered during a single operation. In addition, it is necessary to use qualified operators to guarantee that data of a superior caliber is being gathered, as the dependability of the inspection is contingent upon a significant degree of attention paid to the operations involved in flight planning, sensor calibration, and data gathering. It is of the utmost importance to tackle these difficulties in order to take full use of the possibilities that unmanned aerial vehicle technology has to offer in contemporary pavement monitoring and management tactics [51].

2.3 LITERATURE REVIEW ON THE EVOLUTION OF PHOTOGRAMMETRY USING UAVS FOR FLEXIBLE PAVEMENT INSPECTION:

2.3.1 Early UAV-based Photogrammetry (Limited Accuracy and High Dependency on Manual Work)

During the beginning stages of pavement inspection using photogrammetry based on unmanned aerial vehicles, the technical tools and gadgets that were employed for aerial photography and photogrammetric analysis were still in their basic and primitive forms. Due to the fact that the initial uses of unmanned aerial vehicles for pavement evaluation were dependent on low-resolution cameras and rudimentary photogrammetric algorithms, the accuracy and the level of detail in the data that was gathered were both restricted. Because automated processing methods and sophisticated image analysis techniques had not yet been developed, these early systems needed to be manually operated to a large extent in order to analyze photos and extract information that was significant [52].

Despite the presence of these constraints, these first endeavors formed the groundwork for the creation of technologies based on unmanned aerial vehicles that are utilized for pavement assessment. Despite the fact that the systems were confined by the technological capabilities of the time, the early applications highlighted the promise of unmanned aerial vehicles to give aerial viewpoints and to increase the efficiency of visual surveys. These pioneering endeavors were crucial in the identification of the areas that need development, such as the requirement for imaging with a better resolution, photogrammetric processing that was more advanced, and a decreased reliance on the manual interpretation of data [52].

The vast majority of the first-generation unmanned aerial vehicles that were deployed for the purpose of pavement inspection were outfitted with entry-level digital cameras, which placed a substantial restriction on the resolution and clarity of the images that were taken. In the past, a significant amount of human participation was necessary for the operation and data administration of these unmanned aerial vehicles. As a result, the inspection process was carried out with a considerable amount of manual work [53]. It was required to perform a great deal of post-flight processing and data analysis in order to properly make use of the aerial photographs and to extract information that was significant; this was due to the restrictions that were there [54].

During this first period, there were a number of different elements that were responsible for the frequent occurrences of both accuracy and precision impairments. Among these issues were the limited camera capabilities, the instability in flight, and the low-resolution photography, all of which constrained both the quality of the images and the coverage they were able to provide. The limits that were already in place were made worse by the fact that unmanned aerial vehicles (UAVs) were frequently operated at lower altitudes and slower speeds. Because the picture stitching process was laborious and took a long time to complete, it made data processing even more difficult. This procedure consists of combining a number of different photographs into a single unified model. In addition to this, the photogrammetry software that was available at that point in time was not sufficiently developed, and it often resulted in three-dimensional models that were incorrect or not dependable [55].

The majority of the picture interpretation was conducted using manual input since there were no technologies available that could allow real-time analysis or on-the-fly processing. As a result, the outcomes were susceptible to errors caused by humans. These initial difficulties underscored the limits of unmanned aerial vehicles (UAVs) of the first generation; nevertheless, they also offered vital information that was crucial in the development of more sophisticated, higher-precision unmanned aerial vehicle-based inspection systems throughout the years that followed [53].

Despite the many limits, limitations, and developmental hurdles that were connected with the original deployments of unmanned aerial vehicles, these early applications were able to effectively show the promise of UAV-based photogrammetry for the examination of pavement. They discovered that unmanned aerial vehicles have the potential to lower the dangers and threats to safety that are intrinsic to conventional manual road inspections. This is especially true when it comes to decreasing the necessity for workers to be physically present on the pavement. Unmanned aerial vehicles shown that they are capable of covering greater regions and more extensive territories in a more efficient manner than traditional inspection approaches. This finding indicates that UAVs possess a considerable advantage in terms of both scale and operational coverage [56].

Despite the encouraging findings and the advantages that were seen in the early stages of operation, the technologies that were based on unmanned aerial vehicles were still viewed by the majority of people as experimental instruments or technological novelties as opposed to totally dependable and widely used operational systems. The early deployments highlighted the necessity for continued enhancements in camera resolution, flying stability, image processing algorithms, and automation in order to transition unmanned aerial vehicles from experimental platforms to reliable instruments for the regular evaluation of pavement conditions. [56].

2.3.2 Improved UAVs with Higher Resolution Cameras and Basic Automation (Mid-2000s to Early 2010s)

Beginning in the middle part and central portion of the 2000s, significant progress and major advancements had been achieved and accomplished in the underlying technology and foundational systems that support and drive unmanned aerial vehicles (UAVs). The development and evolution of UAV platforms that were more stable, steady, and reliable, combined with the advancement and improvement of high-resolution and high-quality cameras, led to noticeable improvements and enhancements in both the quality and clarity of aerial photographs as well as the dependability and reliability of pre-planned flight paths and navigational routes. With these technological upgrades and equipment enhancements, it became increasingly possible and more likely that orthophotos and three-dimensional (3D) models used in pavement research and surface evaluation would exhibit better clarity and greater detail, especially when the UAVs were able to capture and collect images from a wider variety and broader range of angles and perspectives [57,58].

Furthermore, and in addition to hardware improvements, during this same time period and developmental phase, significant enhancements and notable improvements were made to the software programs and digital applications that are used in photogrammetry techniques and image-processing workflows. The incorporation and adoption of additional techniques and extra processing methods had the direct effect and noticeable impact of making the image-stitching process more automated, streamlined, and less dependent on manual input. This automation, in turn, resulted in a reduction and decrease in the overall time and effort required for post-processing operations and data refinement. However, despite these advancements and improvements, UAVs still remained relatively limited and somewhat constrained when it came to conducting large-scale and wide-area pavement inspections. Their limitations in battery capacity, flight duration, and data processing speeds continued to pose difficulties and present obstacles, which ultimately hindered their effectiveness and efficiency in more extensive inspection projects. Pavement inspections, under these conditions, still posed a considerable and significant challenge for UAV technologies [59].

Despite these persistent limitations and ongoing technical challenges, the photogrammetric models that were produced and generated during this era and timeframe continued to face issues and difficulties related to image misalignment, distortion, and geometric inaccuracies particularly when they were applied to and used for evaluating pavement surfaces that were highly textured or irregular. This was especially true and particularly evident during the period and phase under consideration. Nevertheless, these UAV-based systems gradually began to provide and offer a more complete, holistic, and detailed view of pavement conditions and surface integrity. One of the major benefits and key advantages of these systems was their growing capability and increasing potential to identify and detect visible pavement distress, such as surface cracks and potholes, more effectively and accurately than many previous ground-based methods and traditional inspection techniques [60].

Despite the fact that UAVs were still faced with and confronted by a range of operational difficulties and functional limitations, they began to gain recognition and acceptance as viable and effective tools for pavement evaluation and maintenance activities during this time. The transition and gradual shift from completely manual UAV inspections to semi-automated, partially autonomous UAV inspection systems began to take place and unfold during this developmental stage and technological phase [61].

2.3.3 Integration of Advanced Sensors and Real-Time Data Processing (Late 2010s)

Over the course and span of the latter portion and final segment of the 2010s, photogrammetry systems that were developed and founded on the use of unmanned aerial vehicles began to incorporate and integrate more advanced, cutting-edge sensors along with capabilities for real-time data acquisition and instant information processing. Unmanned Aerial Vehicles started to be equipped and outfitted not only with high-resolution, high-definition cameras, but also with supplementary tools and advanced devices such as LiDAR (Light Detection and Ranging) sensors and thermal imaging cameras [62-64]. This combination and integration of technologies significantly enhanced and expanded their ability and potential to detect, identify, and analyze surface-level flaws and deeper structural damages. These innovations were implemented and adopted primarily to save both time and cost, making the inspection process faster and more economically efficient [65].

During this particular time frame and technological phase, there was a notable and visible reduction and decline in the need for manual labor and human involvement in the post-flight image processing stage. This was a direct result and natural consequence of the increasing use and application of artificial intelligence systems and machine learning algorithms. The inclusion and integration of such intelligent technologies made it possible and achievable to automatically detect and recognize pavement-related distress. Furthermore, these smart systems were capable of classifying and categorizing different types and forms of surface damage-including, but not limited to, cracks, potholes, rutting, and surface irregularities, which led to a marked improvement in both the overall reliability and general consistency of the inspections, as well as the speed and efficiency at which those inspections were carried out [48,66,67].

In addition to these advancements, there were also noticeable improvements and extensions in the battery life and energy efficiency of unmanned aerial vehicles. This battery enhancement enabled longer operational durations and allowed inspections to cover and assess larger and broader pavement sections. As a direct result and consequence of this upgrade, it became easier and more manageable to conduct high-throughput evaluations and large-scale assessments in a single session or flight, without constant interruptions or recharging delays.

However, despite the substantial improvements and significant advancements made in this field and area of study, UAV-based photogrammetry systems still continue to face and encounter several ongoing challenges and persistent obstacles. Among the remaining difficulties are factors such as dependence on favorable weather conditions, limitations in flight duration and operational range, and occasional difficulty in accurately capturing and analyzing complex pavement characteristics, especially in difficult or demanding environments such as high-traffic urban zones and congested roadway areas. These represent just a few examples of the challenges and complications that continue to arise and persist in UAV-based pavement inspection applications.

2.4 RELATED WORKS

A comprehensive and detailed photogrammetric approach was employed in order to analyze road pavement deterioration with a relatively high level of accuracy and spatial precision. The researchers utilized a Phantom 4 Pro, a widely used and commercially available unmanned aerial vehicle, to capture a series of two-dimensional aerial photographs of the targeted pavement surface. These images were acquired under specific flight parameters and environmental conditions designed to maximize image quality and ensure consistency across the dataset. Once the images were successfully collected, they were processed using two prominent photogrammetry software platforms: Pix4D and Agisoft Photoscan (now known as Agisoft Metashape). These software applications are widely recognized in the field of remote sensing and 3D modeling for their ability to generate high-resolution digital surface models and orthophotos from overlapping 2D imagery.

Through this image processing workflow, a detailed three-dimensional reconstruction of the pavement surface was generated. This 3D model was produced with an impressive spatial precision of approximately 1.54 centimeters, meaning that the model's data points accurately reflected real-world measurements within that margin of error. Such a level of detail allowed for an in-depth and nuanced analysis of surface conditions. Once the 3D model was created and verified for accuracy, it was subsequently processed using a custom-developed or pre-existing analytical algorithm designed specifically to detect and quantify various types of surface deterioration. The algorithm performed a series of calculations and geometric assessments to determine both the degree and extent of degradation that had occurred on the road surface.

Throughout the entire procedure from image acquisition and photogrammetric processing to algorithmic deterioration analysis an overall error margin of approximately one centimeter was observed. This relatively low error rate underscored the effectiveness and reliability of the UAV-based photogrammetry approach used in the study. The final output of the process included two key pieces of information: first, the quantitative measurement of the level of degradation observed (such as the depth and severity of cracks, rutting, or deformation), and second, the spatial extent or area coverage of the deteriorated regions. In other words, the model provided not only precise numerical indicators of the damage but also a clear visualization of where on the pavement the damage was located and how much surface area it affected. This type of data is extremely valuable for infrastructure monitoring and maintenance planning, as it enables engineers and decision-makers to prioritize repairs, estimate costs, and assess road safety more effectively than traditional manual inspection methods.

Feitosa et al. [12], an extensive body of research literature comprising a total of 131 academic and technical publications was carefully examined, analyzed, and synthesized with the specific intent of evaluating the existing applications of unmanned aerial vehicles in the field of pavement inspection and infrastructure monitoring. This in-depth investigation was narrowly focused on the practical use of UAV technologies in the context of transportation infrastructure, particularly emphasizing road surface evaluations and pavement condition assessments. The primary goal of the study was to determine how UAV-based methods have been adopted, developed, and implemented across various research efforts and case studies, especially in terms of their methodologies, data collection techniques, and overall performance in identifying and analyzing pavement distress.

Following the initial screening and comprehensive evaluation of all 131 documents, the researchers applied a more stringent and targeted selection criterion to isolate only those publications that were directly related to the use of UAVs for the specific task of collecting image and sensor data for the evaluation of pavement surfaces within transportation infrastructure systems. After filtering the sources based on relevance, methodological alignment, and research focus, a final group of thirteen high-quality and thematically appropriate papers was identified and selected for closer review and comparative analysis. These selected papers represented the most focused and substantial contributions to the niche area of UAV-enabled pavement inspection, offering valuable insights into data acquisition techniques, sensor technologies, flight planning strategies, and image-processing workflows used in previous studies.

One of the major outcomes and widely agreed-upon conclusions drawn from this systematic literature review was that the most effective and technically appropriate method for capturing aerial imagery for pavement inspection purposes involves acquiring photographs in a vertical orientation, meaning the camera should be positioned at a nadir angle of ninety degrees directly perpendicular to the surface being imaged. This vertical or nadir-oriented image acquisition approach was found to provide the clearest, most geometrically accurate, and distortion-free images, which are essential for producing reliable photogrammetric outputs such as orthomosaics and 3D models. The vertical perspective minimizes errors related to perspective distortion and parallax, thereby enhancing the accuracy of feature extraction and measurement.

In addition to insights on optimal image acquisition techniques, the review also highlighted important findings from the most recent and up-to-date studies regarding the level of spatial and depth accuracy achievable through UAV-based three-dimensional pavement inspection methods. Specifically, the results indicated that, under ideal conditions and with the proper use of high-resolution imaging sensors and advanced photogrammetric processing software, it is possible to attain an accuracy level of approximately one centimeter. This finding applied to both two-dimensional measurements, such as length and width of pavement cracks or distresses, and depth-related measurements, such as rutting depth or pothole volume, derived from digital surface models (DSMs) and 3D reconstructions. This level of precision reinforces the growing potential of UAV-based systems to serve as viable alternatives or even superior tools to traditional, ground-based pavement inspection techniques, especially in terms of efficiency, safety, and coverage.

Through this extensive literature review, Feitosa et al. effectively demonstrated that UAV technology has not only matured significantly over the past decade but also holds great promise for future applications in automated, high-accuracy pavement assessment, especially when integrated with modern photogrammetry and machine learning tools. The study provides a foundational reference point for researchers and engineers aiming to improve or adopt UAV-based workflows in the context of transportation infrastructure management and road condition monitoring.

Romero-Chambi et al. [9] explored and rigorously examined the potential and effectiveness of utilizing three-dimensional surface models generated from imagery collected by unmanned aerial vehicles for the specific purpose of analyzing and evaluating flexible pavement structures. Their study centered around the acquisition of UAV-captured photographs taken at multiple flight elevations, encompassing a variety of altitudes and viewing angles in order to test the influence of flight height on model accuracy and surface resolution. By capturing images at various levels above the ground surface, the researchers aimed to determine how elevation impacts the quality, fidelity, and spatial accuracy of the resulting 3D reconstructions, which are essential for a reliable assessment of pavement condition.

Using advanced photogrammetric techniques and specialized image-processing software, the researchers transformed the two-dimensional photographs into detailed three-dimensional surface models. These models allowed for a more comprehensive analysis of the structural and surface characteristics of the pavement, going beyond simple visual inspection to include depth and volume-related measurements. Through this process, they were able to effectively recreate the topographic and geometric details of the pavement surface with remarkable precision. Their findings revealed that it is indeed possible to use UAV-derived 3D models to assess and evaluate three-dimensional features and deformations in flexible pavements, such as undulations, rutting, potholes, and cracks, with a spatial accuracy of approximately one centimeter. This level of accuracy was consistent across multiple elevation profiles, demonstrating the robustness of the methodology under different UAV flight conditions.

The significance of achieving such a fine level of accuracy cannot be overstated, particularly in the context of pavement evaluation, where even small deviations in surface elevation can indicate underlying structural deficiencies or early signs of distress that may compromise the integrity and longevity of the roadway. The ability to capture such detailed information non-invasively and efficiently from the air offers a compelling alternative to traditional ground-based inspection methods, which are often labor-intensive, time-consuming, and limited in scope.

The researchers further noted that this UAV-based 3D modeling approach holds tremendous promise in addressing and potentially solving several of the critical challenges that are frequently encountered in the realm of road maintenance and infrastructure management. These challenges include the need for rapid data acquisition over large and inaccessible areas, minimizing disruption to traffic flow, reducing inspection costs, and improving worker safety by limiting the need for physical presence on active roadways. By providing a scalable, accurate, and repeatable method of pavement assessment, UAVs equipped with high-resolution imaging systems and advanced photogrammetric processing tools are positioned to revolutionize how road maintenance strategies are planned and executed.

Ultimately, this work underscores the importance of integrating innovative technologies like UAV-based 3D modeling into modern infrastructure evaluation workflows. It highlights how aerial remote sensing and photogrammetry are not just theoretical tools but practical, field-tested solutions that can contribute meaningfully to improving the efficiency, accuracy, and responsiveness of pavement management systems. Their study serves as an important reference point for further research and real-world implementation in both urban and rural transportation networks, paving the way for more intelligent and data-driven approaches to infrastructure maintenance.

Concentrated their investigative focus on the deployment and integration of unmanned aerial vehicles (UAVs), commonly referred to as drones, in conjunction with cutting-edge deep learning algorithms. Their study aimed to explore how this powerful technological combination could serve as a transformative solution for the detection, analysis, and classification of pavement distress and other roadway anomalies. The researchers emphasized the urgent need for more automated, intelligent, and scalable tools in the field of road infrastructure management tools that can reduce both the cost and time associated with traditional manual inspection methods while simultaneously increasing reliability and precision. As part of this exploration, the study provided a practical case study that applied the PANGEA multi-agent system, an advanced artificial intelligence (AI)-driven framework designed to manage autonomous data collection and interpretation processes across multiple agents or modules.

The case study involving the PANGEA system served as a concrete demonstration of the capabilities and performance of drone-deep learning integration in real-world conditions. In this system, UAVs functioned not merely as passive data collectors but as active components of a coordinated, semi-autonomous inspection workflow capable of navigating pre-defined routes, capturing high-resolution imagery of pavement surfaces, and transmitting that data for real-time or near-real-time analysis. The collected visual data was processed using sophisticated deep learning models trained to recognize and differentiate various types of pavement damage, such as alligator cracking, longitudinal and transverse cracks, potholes, rutting, and surface disintegration.

One of the most remarkable outcomes of the study was the exceptionally high level of accuracy achieved by the detection system. The researchers reported that the deep learning algorithms, when integrated within the PANGEA multi-agent system, attained a predictive accuracy exceeding 95%. This performance benchmark not only validated the technical robustness of the approach but also showcased the potential for such systems to be scaled up and adapted for broader applications in national or municipal road inspection programs. The high accuracy rate implied a significant reduction in false positives and false negatives, which is a crucial factor in ensuring that pavement management decisions are based on reliable, data-driven insights.

The significance of this study extends well beyond the demonstration of technical performance. By achieving this level of efficiency and accuracy, Silva et al. laid the groundwork for rethinking how infrastructure assessment could be conducted in a more cost-effective, scalable, and intelligent manner. Their work highlighted the feasibility of shifting from reactive to proactive maintenance strategies, wherein roads can be monitored more continuously and comprehensively, and small defects can be detected and addressed before they evolve into more severe and costly issues. The automated nature of this system also suggests the potential for reducing the human labor burden typically associated with infrastructure monitoring while simultaneously improving safety by minimizing the need for personnel to operate in hazardous environments such as active roadways.

Furthermore, the study serves as a significant milestone in the ongoing evolution of smart city infrastructure, where autonomous agents, machine learning models, and UAVs work in unison to manage and maintain public assets more intelligently. The authors framed their findings as a clear indicator that innovation in both detection models (deep learning networks) and data acquisition strategies (drone systems) is not only possible but already proving highly effective. Their conclusions pointed toward the future expansion of such systems, encouraging further interdisciplinary collaboration between computer scientists, civil engineers, and transportation planners to refine these technologies and adapt them to a variety of environmental and logistical contexts.

Nappo et al. [68] developed for identifying asphalt road pavement degradation that was established through the process of creating a hotspot map using three-dimensional point clouds. It was possible to successfully identify spots that had significant deviations from the reference road surface, which were places where anomalies were predicted to occur. This technique was successful in detecting these locations. In order to confirm the effectiveness of the approach, it was proven that the suggested methodology had a high degree of consistency with the damage that was personally identified. In spite of the fact that the multi-criteria classifier was shown to be capable of identifying longitudinal and transverse fractures that were wider than one centimeter, there were also some occasions in which it produced false positives. These mistakes were mostly caused by a number of variables, the most important of which were random noise in the point cloud, the presence of concrete structures or ditches at the road boundaries, and tiny cracks that the approach was unable to identify in their entirety. Based on the findings, it appears that the method is capable of identifying road damage in an effective manner without making any prior assumptions about the kind of damage or the precise position of the harm. On the other hand, more testing is required in order to optimize the thresholds for point clouds that have varying densities and resolutions.

Most previous studies agreed that adding ground control points is expected to increase the accuracy of the generated models, mainly for use on road pavement that includes features or reference points that are accessible before taking images [9,11,12,69,70].

In the field of mapping, unmanned aerial vehicle technology has become one of the most quickly emerging technologies and one of the most widely employed technologies. UAVs are widely used in civilian applications as well as applications for the Department of Survey and Mapping [39,71]. Therefore, in order to guarantee accuracy while using a UAV to inspect flexible pavements by using ground control points [9,11,12,53]. This will increase the accuracy of the images that are used to identify pavement issues such as cracks, potholes, and pavement surface erosion [45]. The utilization of photogrammetry software can facilitate the production of georeferenced orthomosaics, elevation models, or 3D models of the designated project area through the processing of relevant data. The maps can be employed for data extraction purposes, such as obtaining volumetric measurements or extremely accurate distances. Drones are able to fly at far lower altitudes than manned flights or satellite imagery, which allows for the collection of high-resolution, high-accuracy data that is significantly quicker, less expensive, and independent of climatic factors such as cloud cover [72,73].

3. METHODOLOGY

The method that was employed in this inquiry is a structured technique that makes use of ground control points (GCPs) and photos obtained from unmanned aerial vehicles (UAVs) in order to evaluate the level of distress that is present on flexible pavement [53]. Furthermore, in order to ensure that the results are credible, it involves both data processing and fieldwork responsibilities. The technique begins with an examination and planning of the site, and then it proceeds to the gathering of data and the capturing of photographs through the utilization of unmanned aerial vehicles (UAVs). After that, the data is processed using the application Agisoft Photoscan to build a three-dimensional model, which is then analyzed to detect and quantify the amount of pavement distress. This procedure is repeated until the desired results are achieved. The precise technique that is applied in this strategy is described in the following steps, which are all included in this strategy.

3.1 STUDY AREA

The selected research location is a portion of the road that can be found in Palestine at the intersection of Al Dhahrieh International Stadium Street and Hebron Street (Figure 3.1). To be more specific, the beginning of the study area is located at a geographical place positioned at 31° 25' 22.8" North and 34° 57′ 06" East. On the other hand, the end of the study area is located at 31° 25' 12.8" North and 34° 56′ 24.6" East. The rationale behind choosing this particular street segment stems from several important logistical and technical factors. First and foremost, the selected road experiences significantly lower vehicular traffic volumes in comparison to the nearby primary roads and highways that serve as main transit corridors for the city. This relatively low traffic density greatly reduced the risks and logistical complications associated with field operations, such as UAV takeoff and landing, GCP installation, and manual pavement inspection activities. The reduced traffic also minimized the potential for motion-induced distortion in UAV imagery, as fewer moving vehicles on the surface result in fewer interruptions and visual obstructions during aerial data acquisition.

Another factor that reinforced the suitability of this location was the ease of access for the research team, as the area is situated near the urban perimeter of Al Dhahrieh and is adjacent to a public facility, the International Stadium, which allowed for the secure staging of UAV equipment, surveying instruments, and personnel. This proximity also ensured that any required calibration, system maintenance, or re-deployment could be conducted efficiently and with minimal disruption.

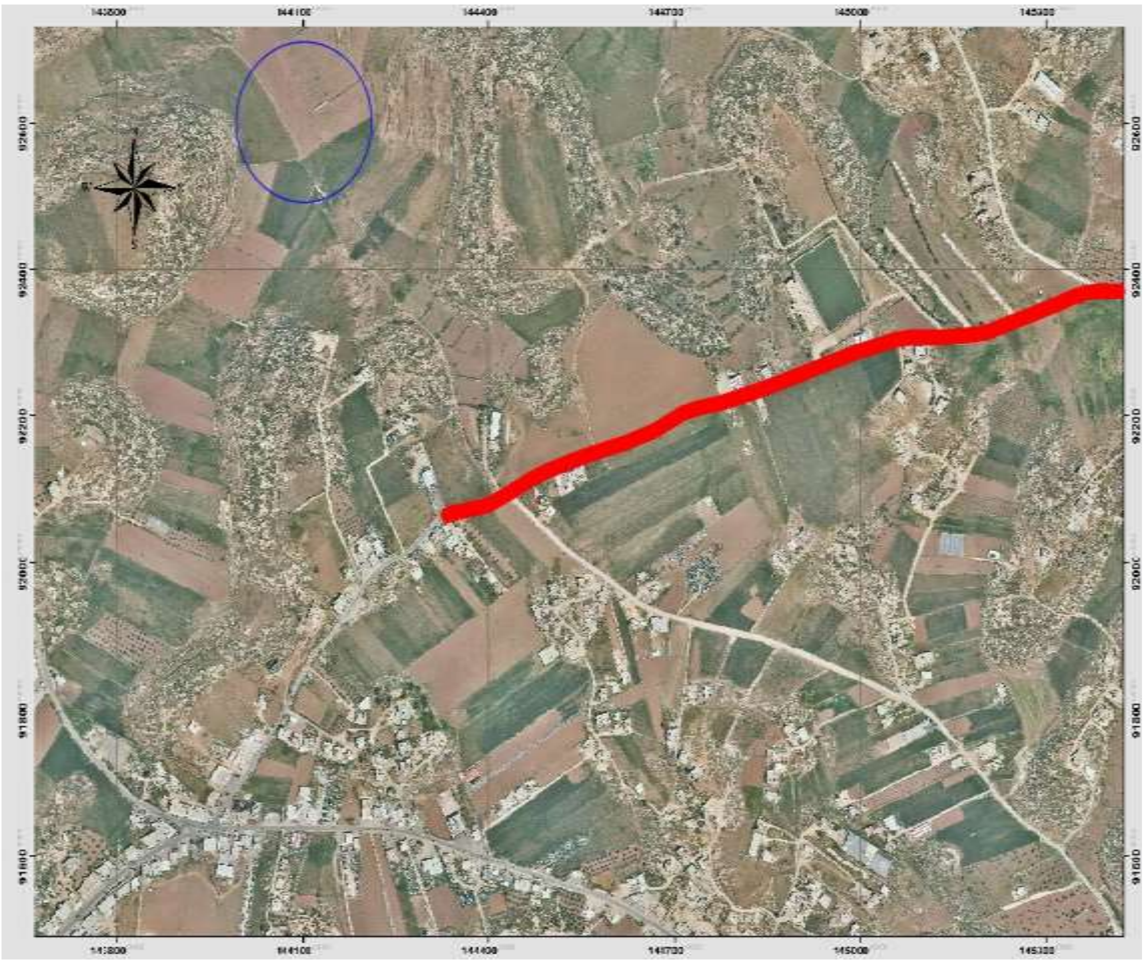


Figure 3.1: Study Area, Source(Al-Dahrieh Municipality)

The surface quality of the pavement that was selected for this study was subpar, which resulted in a substantial amount of trouble for the people who used it in the neighborhood that surrounded it. It was discovered that there were several different kinds of distress, such as cracks that were longitudinal, transverse, and crocodile in shape, as well as places that were patched and rutted. Not only did these problems result in an uneven surface, but they also presented a threat to the safety of those who used the road. An additional factor that contributed to the degeneration of the pavement was the fact that the cracks, particularly the crocodile cracks, were prevalent, and the patches that were utilized for repairs were deteriorating. Clearly visible rusting could be seen in the wheel grooves, which made the damage much worse. A selection of these distresses is depicted in Figure 3.2, which provides an illustration of the degree to which the pavement has deteriorated.

Figure 3.2: Sample for Ruts, Patches, and Cracks.

3 .2 RECONNAISSANCE AND PLANNING

Following the identification and definition of the study area boundaries, the next critical phase in the data collection process involved conducting a thorough examination of the physical characteristics and surface conditions of the site. This included an assessment of the topography, such as the natural elevation changes, slope variations, and any surface irregularities that might affect UAV flight performance or the accuracy of photogrammetric outputs. Additionally, the condition of the pavement itself was carefully studied to understand the distribution and severity of surface distress features, which would later be analyzed through aerial imagery [5]. Based on this preliminary investigation, strategic decisions were made regarding the placement of Ground Control Points (GCPs) within the study area. These GCPs were positioned to ensure complete spatial coverage of the site, including all relevant elevation changes, and to promote uniform distribution across the entire area. This was done to enhance the georeferencing accuracy of the photogrammetric models, both in the vertical and horizontal dimensions. The layout and spread of the GCPs, which were intentionally arranged to cover the periphery as well as the interior sections of the study zone, are clearly illustrated in Figure 3.3.

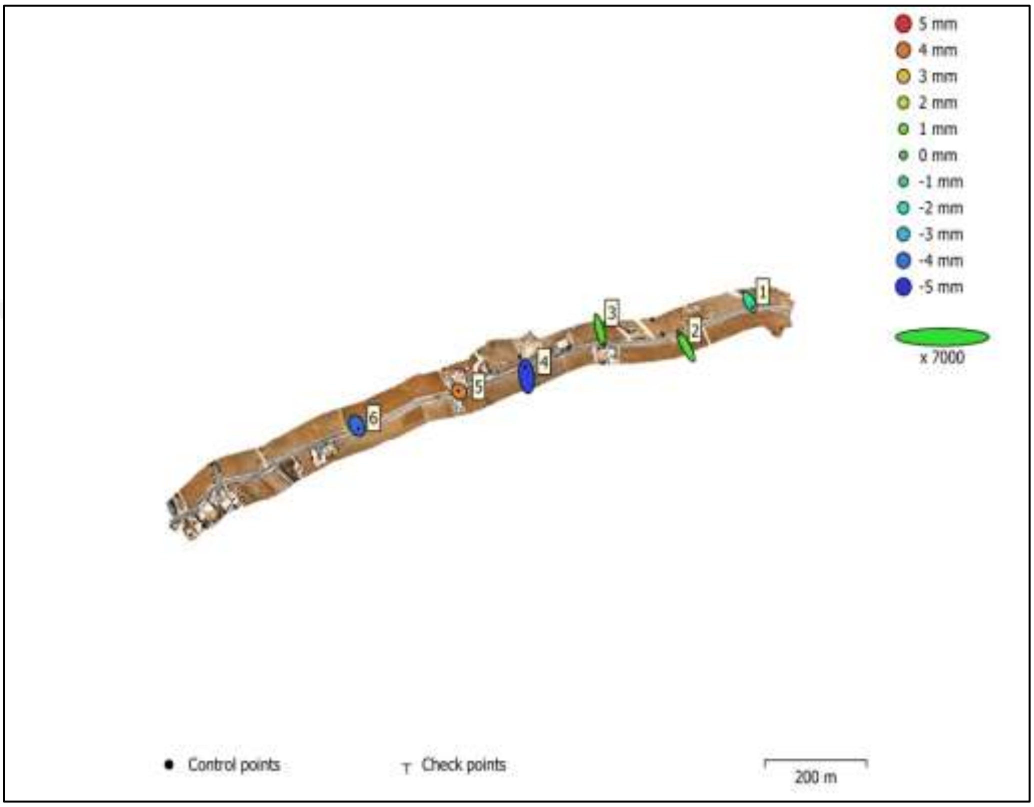
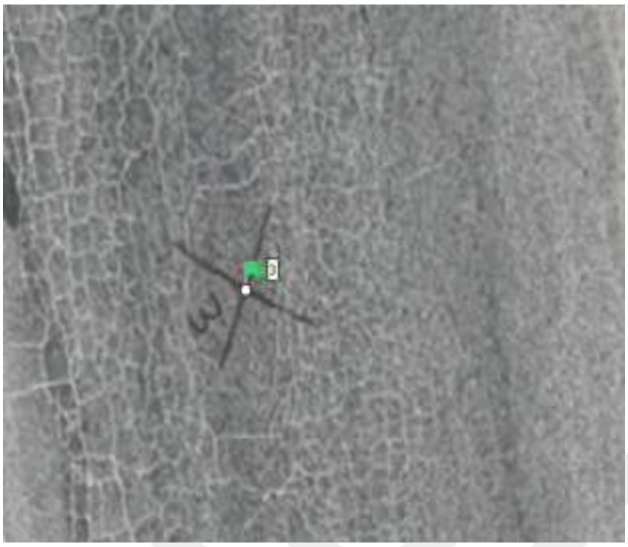


Figure 3.3: Gcps Locations and Error Estimates.

Once the optimal locations for the GCPs were identified, the next step was to mark these points directly on the pavement surface. This was accomplished using highly visible natural or artificial features that could be easily distinguished in the aerial imagery. Examples of such features included intersections of visible cracks, sharp pavement edges, unique stain patterns, and other distinct markers that stood out in both the field and the orthophotos. This approach allowed the GCPs to be recognizable in the post-processing phase[68], as illustrated in Figure 3.4 b). After physically marking the points, each GCP underwent high-precision spatial surveying using a Spectra Precision SP60 GNSS device, a geodetic-grade GPS receiver known for its ability to produce centimeter-level accuracy even under challenging environmental conditions. This instrument, as shown in Figure 3.4 a), out the area to serve as verification references. These checkpoints were later used to assess the geometric accuracy and reliability of the orthophoto and 3D model outputs generated during the photogrammetric processing stage [5].



A) B)

Figure 3.4: a) Spectra Precision SP60 GNSS Device, b) Gcps Marking.

The recorded coordinates of all GCPs, obtained through the GNSS receiver using real-time kinematic (RTK) correction methods, were stored for integration into the photogrammetry software. These precise location values were vital for aligning the UAV imagery to true ground coordinates and minimizing errors in the final model. The full list of the GCPs' geographic positions is documented and presented in Table 3.1, serving as an essential reference for both the reconstruction process and the subsequent validation of results.

Table 3.1: Gcps Coordinates. (With Palestine 1923 / Palestine Grid (EPSG::28191) Coordinate System.

Points	Easting	Northing	Height/Elevation
C1	145374.615	92370.085	634.651
C2	145231.011	92321.820	629.327

Table 3.1: Gcps Coordinates. (With Palestine 1923 / Palestine Grid (EPSG::28191) Coordinate System. "Table Continued".

C3	145081.412	92305.848	628.150
C4	144927.754	92265.035	626.278
C5	144795.499	92223.948	623.577
C6	144600.311	92157.798	624.056

3.3 DATA COLLECTION

3.3.1 Manual Methods For Flexible Pavement Inspecting

Pavement inspection activities were primarily conducted through traditional manual techniques, which remained the dominant method before the widespread adoption of modern technologies. These manual inspection procedures involved a labor-intensive and systematic approach, where the roadway under assessment was divided into multiple inspection units. This segmentation was typically carried out both longitudinally and transversely along the length and width of the pavement in order to ensure a thorough and structured evaluation of surface conditions [53,74]. Each unit served as a defined zone within which specific measurements and observations would be recorded to determine the type, severity, and extent of various pavement distresses.

To carry out these inspections, a range of simple yet essential hand tools was utilized. Among the most commonly used instruments were the ruler and the straight edge, which allowed inspectors to measure the depth and width of surface deformations, such as ruts and cracks. These tools were vital in determining the severity of certain types of defects. In addition, a measuring tape (meter tape) was employed to obtain the length of ruts or linear cracks, while thread or string was often used in an innovative yet basic manner to outline the perimeter of potholes. The thread would be carefully laid along the boundary of the pothole, allowing inspectors to trace and later calculate the approximate area of the defect [70]. These tools, although simple, required skill and attention to detail to ensure consistent results across multiple pavement sections.

Despite its usefulness, this conventional method of data collection had several critical limitations. Most notably, the process was highly time-consuming and labor-intensive, requiring a substantial amount of manual input from field personnel. In particular, when applied to large-scale road networks or urban streets with extensive damage, the manual inspection process would become especially demanding. Inspectors often had to repeat measurements for accuracy and physically move across multiple units, sometimes under hazardous conditions or during extreme weather. This not only extended the time required for data collection but also introduced the potential for human error, including inconsistent measurements, observational bias, and fatigue-related inaccuracies [70,71,75].

Figure 3.5 provides a visual example of the traditional measurement technique, showcasing how field personnel manually engage with pavement surfaces to identify and record defect characteristics. While this approach laid the foundation for early pavement condition assessment practices, its inefficiencies and limitations have driven the development of modern alternatives, such as UAV-based photogrammetry, which this study aims to explore and evaluate.

Figure 3.5: Sample Of Measuring Rut's Length Manual Method Using Meter and Ruler.

3.3.2 Photographing The Study Area Using UAVs (Drone Survey)

The Unmanned Aerial Vehicle (UAV) system used in this research includes three main components: the quadcopter itself, the digital camera mounted on the drone, and the built-in flight control system that manages its operation. These parts work together as a complete unit designed to capture high-quality aerial images needed for pavement inspection. For this particular study, the DJI Mavic 3 (L2D-20c) Professional UAV system was selected due to its reliability, popularity, and practicality for aerial photography tasks in research applications as shown in Figure 3.6. This specific model has become one of the most widely used drones among end-users and professionals because of its well-balanced combination of performance, simplicity, and affordability [76].

One of the main advantages of the DJI Mavic 3 is that it is very user-friendly, making it easy for operators, even those with limited experience, to fly the drone effectively and safely. Its flight system is designed with ease of use in mind, allowing for stable flights and smooth image capture, which is essential when collecting consistent and clear photographs of pavement surfaces. The Mavic 3 is also known for being lightweight and portable, making it simple to transport and deploy in the field [76].

Another benefit of this UAV system is that it comes fully assembled and ready for use without requiring any custom modifications or technical adjustments. All necessary components such as the GPS navigation system, flight stabilization features, and remote-control unit are included in the set. This integrated design allows the user to begin operations with minimal setup time, which is especially helpful when working in multiple locations or under time constraints. The GPS system in particular, ensures that flight paths are precise and that images can be georeferenced accurately during post-processing.

The digital camera that comes with the DJI Mavic 3 is also a key feature of the system. It provides high-resolution images suitable for detecting cracks, surface deformations, and other signs of pavement distress. This camera, along with the quadcopter's flight stability and GPS accuracy, makes the system well-suited for photogrammetric applications like those used in this study. Together, these features make the DJI Mavic 3 a cost-effective, efficient, and technically capable solution for collecting the aerial data required for evaluating pavement conditions.

Figure 3.6: DJI Mavic 3 (L2D-20c) Drone Features.

Table 3.2 provides a detailed and comprehensive summary of the technical specifications and operational capabilities of the UAV system used in this study, with a particular focus on the characteristics of the cameras integrated into the system for the purpose of data collection. The table outlines the essential features of each camera, including resolution, sensor type, focal length, and other imaging properties that directly influence the quality and precision of the data acquired during the UAV flights. These specifications are critical in determining the suitability of the cameras for photogrammetric applications, especially when high-resolution imagery is required to detect and analyze pavement surface distresses such as cracks, rutting, and potholes.

The inclusion of this information allows for a better understanding of how each component contributes to the overall performance of the UAV system during the image acquisition process. By detailing the camera parameters, Table 3.2 offers a clear picture of the technological tools employed to ensure that the data captured is both accurate and reliable, which is essential for generating high-quality orthophotos and 3D models in the later stages of analysis. Furthermore, presenting the specifications in a structured format allows for easier comparison and evaluation of the equipment, supporting the justification for the system's selection in the context of flexible pavement inspection. This comprehensive overview not only highlights the functionality of the UAV and its imaging components but also reinforces the system's capability to meet the demands of precise, efficient, and large-scale infrastructure monitoring.

Table 3.2: Camera Specifications.

Device	**DJI Mavic 3**
Camera Model	L2D-20c (12.29mm)
Resolution	5280 x 3956 µm
Focal Length	12.29 mm
Pixel Size	3.36 x 3.36
Precalibrated	No

A total of 263 aerial images were captured during the course of this investigation, with all photographs taken from a consistent altitude of 59 meters above the ground surface. These images were obtained using an unmanned aerial vehicle (UAV) system specifically configured for photogrammetric data collection and pavement condition assessment. To ensure that the imagery could be accurately georeferenced and spatially aligned within a defined coordinate system, a total of six Ground Control Points (GCPs) were strategically placed and utilized throughout the study area during field operations.

These GCPs played a vital role in supporting the spatial referencing process by serving as fixed, high-accuracy reference positions on the ground, which were later used to align the UAV-captured images with real-world coordinates. In order to collect precise location data for the GCPs, the Real-Time Kinematic (RTK) technique was employed, which enabled centimeter-level positional accuracy and improved the overall reliability of the final photogrammetric models.

Figure 3.7 presents an example of one of the aerial images captured during the flight mission, offering a visual reference for the type and quality of data acquired. Furthermore, the complete specifications related to the data acquisition process using the UAV system—including flight altitude, image overlap, camera settings, and flight path planning—are detailed in Table 3.3, which provides a clear technical summary of the methods and parameters used during the aerial survey phase of the research.

Table 3.3: The Specification of Collecting Data by UAV**.**

Parameters	**altitude**
Number of images	263
Flying altitude	59.4 m
Ground resolution	1.47 cm/pix
Coverage area	0.109 km^2
Projections	911,796
Reprojection error	1.01 pix

Figure 3.7: Sample Of UAV Images.

3.4 DATA PROCESSING

To carry out the processing of aerial photographs captured by unmanned aerial vehicles, Agisoft Photoscan software is used in a structured two-phase approach. In the first phase, the software is utilized to generate an initial three-dimensional model of the study area without the integration of ground control points.

This preliminary model serves as a base reference and provides a general representation of the surface but lacks high positional accuracy due to the absence of spatial reference anchors. In the second phase, the 3D reconstruction is enhanced through the incorporation of GCPs, which are accurately measured and georeferenced points distributed across the study site. This stage enables the refinement of the model by anchoring it to real-world coordinates, significantly improving the geometric accuracy of the final outputs.

The reconstruction achieved in this phase delivers a model with a ground resolution of 1.47 cm/pixel, ensuring a high level of detail suitable for precise pavement analysis, as illustrated in Figure 3.8. Additionally, the accuracy of the control point integration is quantitatively evaluated by calculating the Root Mean Square Error (RMSE) for each coordinate axis. Table 3.4 presents the RMSE values associated with the X (Easting), Y (Northing), and Z (Altitude) directions, offering a comprehensive overview of the spatial precision attained through the georeferenced model.

This evaluation confirms the effectiveness of the GCP-based photogrammetric workflow in improving the positional reliability of UAV-derived 3D models.

Table 3.4: Control Points Errors & RMSE.

Lable	Easting Error (mm)	Northing Error (mm)	Height/Elevation Error (mm)	Total (mm)	Image (pix)
C1	1.722	-2.630	-1.449	3.462	0.849(4)
C2	-3.427	5.647	0.457	6.622	0.543(4)
C3	1.913	-6.364	0.311	6.653	0.438(4)
C4	-0.632	4..410	-4.744	6.508	1.061(3)
C5	-0.560	0.338	3.745	3.802	0.805(4)
C6	0.975	-1.457	-4.127	4.485	1.761(3)
Total	1.827	4.103	3.054	5.432	0.956

Figure 3.8: Orthophoto With Coordinates System.

Agisoft Photoscan offers a wide range of features that are instrumental in extracting digital elevation models, as shown in Figure 3.9. The production of dense point cloud data is one of its most powerful tools. This data is essential for 3D modeling and spatial analysis, and it is required for both of these processes. The exterior surface of objects in a three-dimensional environment may be precisely captured by dense point clouds, which are made up of millions of coordinate-based data points. These point clouds use X, Y, and Z coordinates to do this.

By accurately describing the geometry of the terrain or structures, these point clouds will serve as the basis for a variety of additional geospatial outputs, such as digital elevation models and contour lines. When it comes to topographic mapping, land surveying, and archaeological recording, each of which needs precise volumetric accuracy and fine details, this data format is very useful [70].

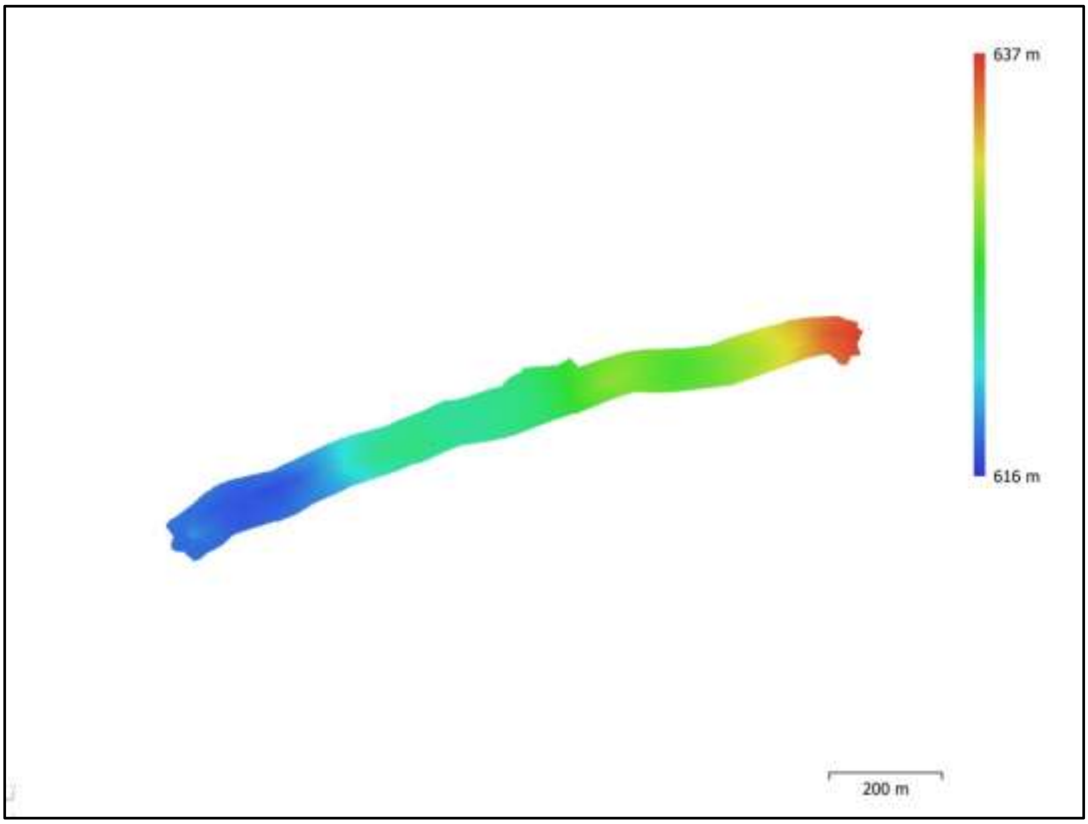


Figure 3.9: Extracted Digital Elevation Models (DEMs).

In addition to facilitating the production of precise three-dimensional models, the dense point cloud also makes it possible to extract specific elevation data, which can then be viewed and evaluated by means of contour lines.

The volumetric data that is represented in the three-dimensional point cloud has the ability to assist in modeling variations in the terrain and identifying small changes in surface characteristics. A high-resolution representation of the surveyed area that guarantees accuracy and dependability is produced as a consequence of the processing of the sophisticated photogrammetric algorithms employed by Agisoft Photoscan. As a result of the direct influence that accurate geographical data has on planning and decision-making, these outputs are vital for professionals working in sectors such as design, building, environmental monitoring, and cultural heritage preservation [70].

3.5 OBTAINING AND ANALYZING RESULTS

This research focuses on evaluating the accuracy and effectiveness of a three-dimensional (3D) model generated from UAV imagery in detecting and quantifying various types of flexible pavement distress, using a relatively limited sample size for assessment. The study involves a comparative analysis between traditional, manual field-based measurement techniques and the model-based approach derived from photogrammetric outputs. Specifically, the 3D model, along with the corresponding orthophoto, was utilized to identify and measure the extent of different pavement distresses, including potholes, patch areas, rutting, and various forms of cracking.

The process of analysis was conducted using the tools available within Agisoft Photoscan software, which allowed for the digitization of polygons to delineate the shapes and areas of potholes and patches, the placement of measurement points at regular intervals to evaluate rutting depths, and the identification of crack regions and types based on the high-resolution imagery embedded in the 3D surface model.

To measure rutting, the software's built-in measuring tool was used to select specific points across the rutting area on the 3D model surface, and the depth values were automatically calculated based on the vertical differences between selected high and low points. In order to verify the accuracy of the digital measurements, rutting depth was assessed using two distinct methods: the conventional field-based measurement method, which involved physical tools and manual inspection, as shown in Figure 3.10 and the digital model-based measurement method derived from the 3D model within the software environment, as shown in Figure 3.11.

The values obtained from the digital model were then compared against the manual measurements, which were treated as the ground-truth reference, and the differences between the two sets of measurements were calculated and analyzed to determine the precision and reliability of the UAV-based 3D model for pavement distress evaluation.

Figure 3.10: Measurement for The Depth Of Rut Using Conventional Methods.

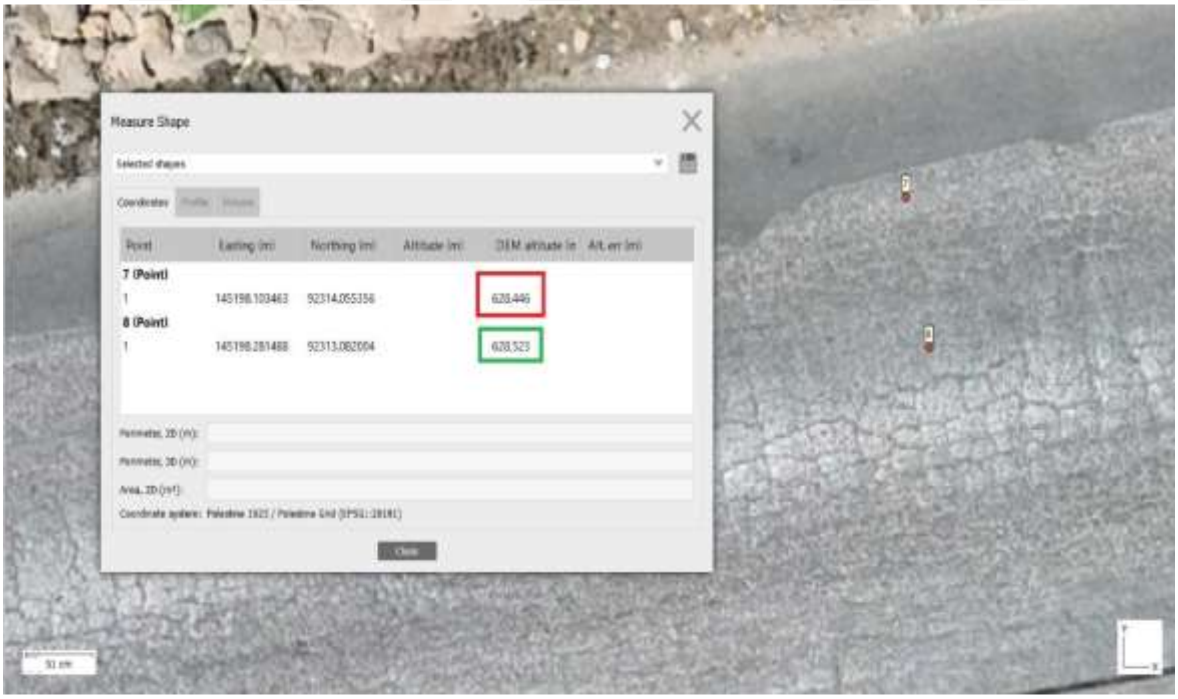


Figure 3.11: Measurement For The Depth of the Patch Using Modal Methods.

These techniques provide an efficient method for finding and measuring surface distress in road pavements, which is a significant benefit. In the course of the installation procedure, the application offers a measuring tool that makes it possible to draw a polygon around the regions that need to be repaired and the potholes that have been created on the 3D model. Immediately after the polygon has been created, the program will automatically determine the size of the region that has been chosen. In the course of the procedure, this will facilitate the acquisition of precise measurements of both patches and potholes.

Conventional field measurements and modal measurements produced via the use of the 3D model are the two ways that are utilized in order to guarantee the accuracy of these measurements. During the traditional technique, measurements are obtained directly in the field, where physical dimensions are recorded manually using proper instruments as shown in Figure 3.12.

During the modal approach, on the other hand, measurements are collected from the three-dimensional model that is formed by the photos captured by the unmanned aerial vehicle (UAV), as shown in Figure 3.13. This model is used to generate the measurements. The photos that are gathered by the unmanned aerial vehicle (UAV) combine to generate this model. Next, the differences between these two approaches are computed, and field measurements are taken into account as the criterion for determining the degree of accuracy. Finally, the results of this computation are shown. As a result of this, it is now possible to evaluate the efficiency and precision of the model-based measurements in contrast to the conventional one that is carried out manually .

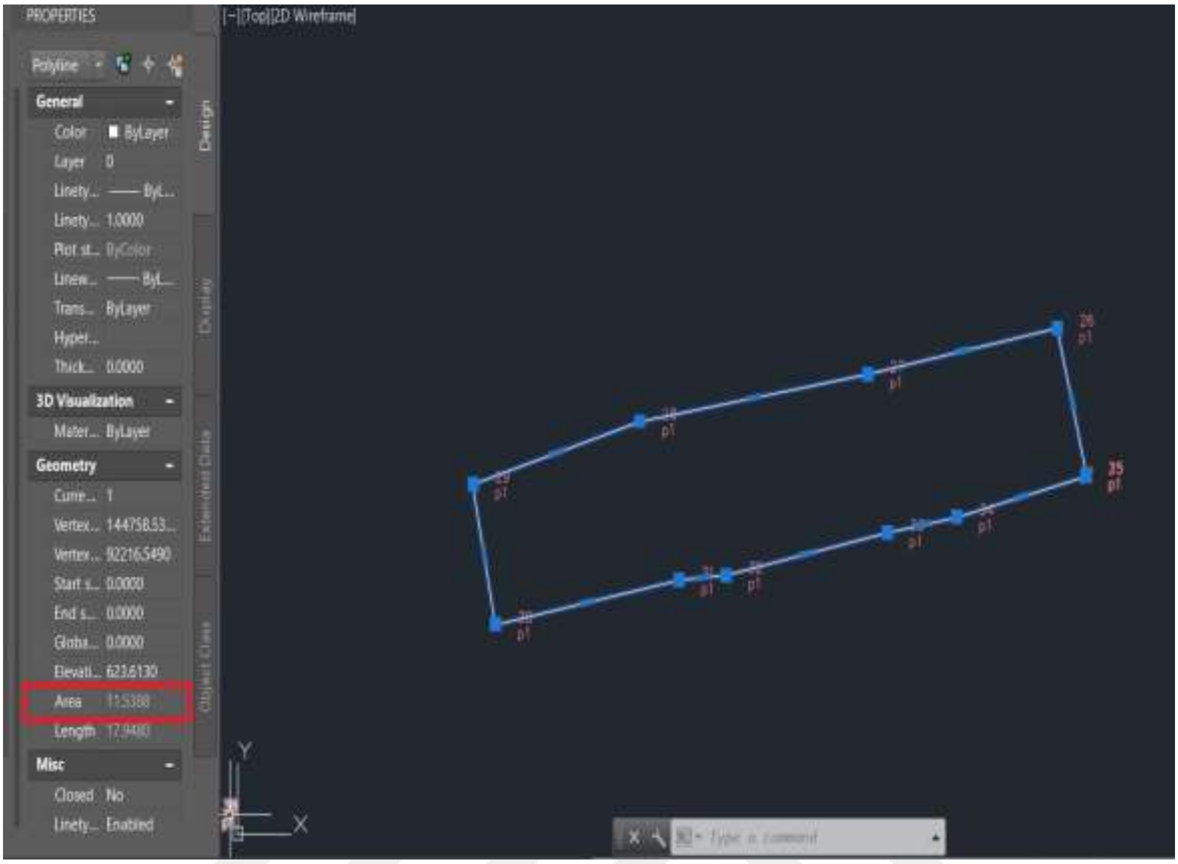


Figure 3.12: Measurement Of The Area of Patches Using the Conventional Method.

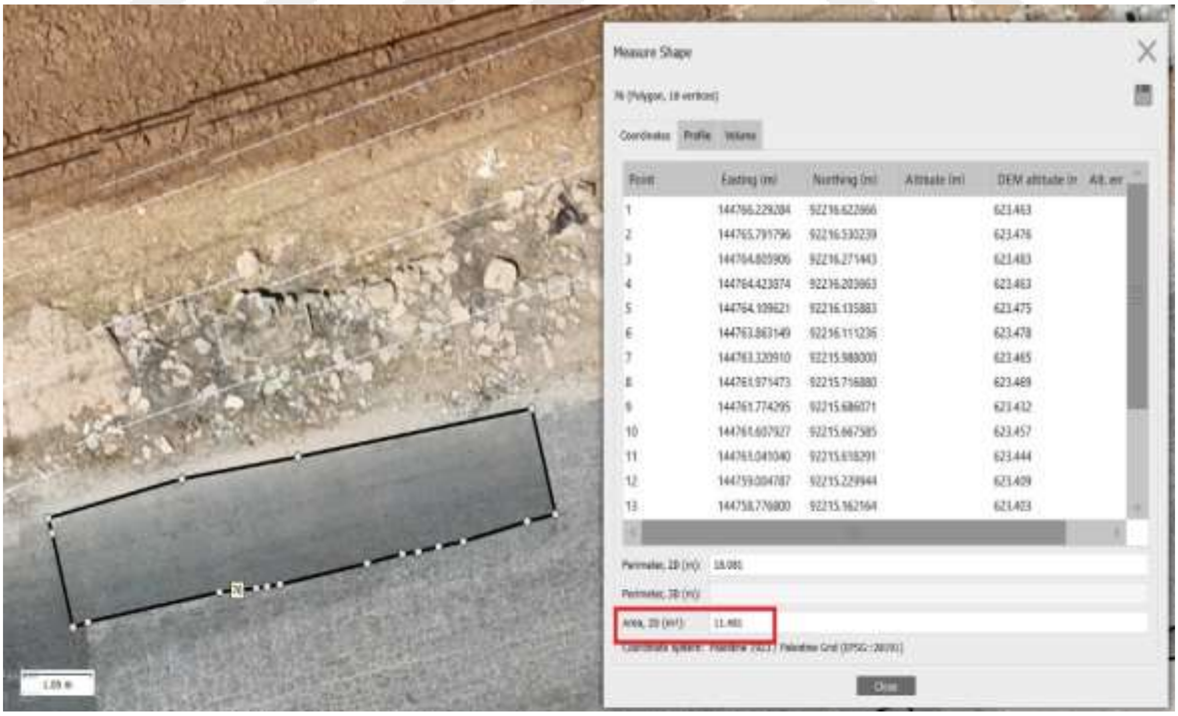


Figure 3.13: Measurement Of The Area of Patches Using the Modal Method.

4. RESULTS AND DISCUSSION

4.1 RESULTS

In Table 4.1, there is a presentation of the full outcomes of the lengths that were measured for rutting in ten pavement samples, which are labeled S1–S10. Also included is a complete analysis of the elevation-error values that are linked with these measurements. The determination of the accuracy of rutting-depth detection in flexible pavements was the goal that was being pursued by the implementation of these measures. The disparities between the reference and measured values were consistently minor throughout all of the samples, as indicated by the findings, which reveal that the least error was 1 mm and the greatest error was 5 mm. The restricted fluctuations that are shown here serve to illustrate the significant level of accuracy that is achieved by the measuring method that is being used.

In order to evaluate the overall accuracy of the system, the Root Mean Square Error was computed for all samples, which resulted in a value of 0.00354 meters. This figure corresponds to an accuracy level of 96.46 percent. The precision of this performance is more than the normal accuracy of traditional measuring techniques, which often exceed 95% [77]. As a result, the credibility and strength of the approach that was utilized in this investigation are verified. The root mean square error value functions as a numerical reference point for the purpose of assessing the quality of measurements and furnishes compelling proof of the system's efficiency.

A more thorough investigation of the outcomes for each sample showed that there were modest differences when compared to the computed root mean square error (RMSE). In particular, the error values of six samples were slightly more than the root mean square error (RMSE), which indicates that the samples showed slight deviations from the anticipated results. The disparities in the field-measurement circumstances, abnormalities on the surface, and elements that are connected to the instrument are all possible explanations for these inconsistencies. On the other hand, four of the samples had error values that were lower than the RMSE, which means that the measurements were more precise and that they closely matched the reference values.

In general, the outcomes that were obtained from the 10 samples demonstrate a high level of accuracy in the measurements. There were only a few cases in which any variations were noticed, and they were of a minor kind. The dependability of the rutting-detection method is further supported by these data, and its appropriateness for making precise evaluations of pavement conditions has been verified.

Table 4.1: Measurement for the depth of rut samples.

Sample NO.	Values from conventional measurement(mm)	Values from modal measurement (mm)	Error(mm)
S1	76	77	1
S2	61	65	4
S3	62	60	2
S4	41	45	4
S5	55	58	3
S6	40	43	3
S7	36	41	5
S8	42	47	5
S9	75	77	2
S10	41	45	4
RMSE = 3.54 mm = 0.00354 m			

In particular, Figure 4.1 demonstrates that the disparities between the two methods the traditional field measurement and the recommended UAV-based model measurement are relatively close. This suggests that both approaches produce findings that are typically equivalent in terms of accuracy.

The findings that were produced from the approach that was recommended, on the other hand, clearly display different advantages, particularly in the identification and measurement of rut depths. A direct comparison of the error margin of the traditional approach with the error rate associated with the recommended method reveals that the error rate associated with the suggested method stays reasonably low and, more significantly, falls well within an acceptable range. When compared to other methods, the conventional technique, which is primarily dependent on manual procedures and the subjective judgment of humans, is intrinsically more likely to produce a greater percentage of inconsistencies and errors. There are a number of factors that can contribute to these inaccuracies, including limits in visual perception, variations in measuring procedures, and human error in data collection. Each of these factors has the potential to compromise the accuracy of the results. Such human-related mistakes are frequently inevitable and have the potential to dramatically diminish the trustworthiness of field-based evaluations, as demonstrated by earlier studies [78,79].

In contrast, the technique that is based on unmanned aerial vehicles (UAVs) that was presented in this study integrates automated and software-assisted measurements that make use of high-resolution imaging and digital modeling. This significantly lowers the effect of human subjectivity and assures a more consistent and reliable data output. An increased level of measurement reliability is achieved via the utilization of the suggested approach, which reduces the amount of manual involvement and makes use of the accuracy offered by photogrammetric equipment. Since this is the case, the comparison study highlights the superior performance of the approach that was recommended, confirming its potential as an alternative that is more accurate, efficient, and reliable for rut depth estimation in pavement condition evaluations.

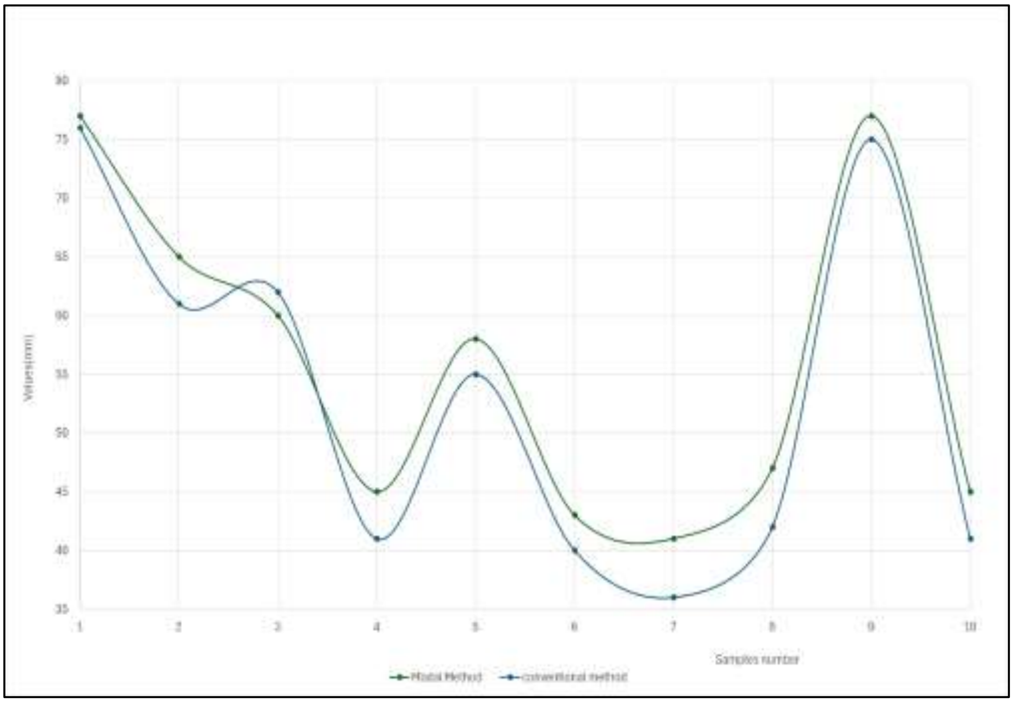


Figure 4.1: Difference in Values of Rut.

Table 4.2 presents the detailed measurements of the patch samples, where ten distinct patch samples were analyzed, labeled Pa1, Pa2, Pa3, Pa4,... Pa5, and the analysis revealed that the Root Mean Square Error (RMSE) for these measurements was 0.000444 m2, which is equivalent to an accuracy rate of 99.6%, highlighting a high level of precision in the measurements compared to conventional measurements, which exceeded 80–85%[77], and suggesting that the margin of error was relatively small across the dataset; this in turn implies that the overall data collected from the patch samples can be considered highly reliable and consistent in terms of measurement accuracy, making them suitable for further analysis or modeling purposes where precision is critical; however, upon a more detailed examination of the individual patch samples, it was observed that three of the samples, showed error values that exceeded the calculated RMSE, indicating that while the overall accuracy of the dataset was high, these particular samples introduced slightly higher levels of discrepancy, which may point to minor inconsistencies in either the measurement process or the conditions under which these samples were collected or analyzed, and thus warrant closer scrutiny in order to determine whether these deviations are due to random variance or if they suggest the presence of systematic errors that could potentially affect the interpretation of the data or the reliability of results derived from it.

On the other hand, seven samples demonstrated error values lower than the RMSE, suggesting that their measurements were closer to the ideal or expected values and, therefore, more accurate in comparison, and this distribution of error values highlights a variation in the accuracy of the different patch samples, with some exhibiting better alignment with the RMSE than others, indicating a level of inconsistency that, while not significantly undermining the overall reliability of the measurements, does point to potential areas for refinement in the measurement process; overall, the findings from Table 4. provide useful insights into the performance and consistency of the patch measurement technique, showing that while the majority of the samples fall within an acceptable error range, there are minor variations that could be addressed for further improvement in accuracy, potentially through enhanced calibration, more controlled sampling conditions, or adjustments to the measurement methodology to reduce the likelihood of such discrepancies in future analyses.

Table 4.2: Measurement for The Area Of Patch Samples.

Sample No.	Values from field measurement(m^2)	Values from the modal measurement (m^2)	Error (m^2)
Pa1	11.538	11.481	0.057
pa2	1.996	2.015	0.019
pa3	58.245	58.136	0.109
pa4	4.146	4.126	0.020
pa5	3.243	3.192	0.051
Pa6	2.516	2.542	0.026
Pa7	2.792	2.782	0.010
Pa8	22.053	22.066	0.013
Pa9	4.768	4.771	0.003
Pa10	2.371	2.356	0.015
RMSE= 4.44 cm2 = 0.000444 m2			

Figure 4.2 demonstrates that the accuracy of the method shown is considered highly acceptable for providing a precise representation of both the dimensions and the area of ruts and potholes. When compared to traditional methods of measuring these areas using various surveying instruments or measurement tools, the results obtained from this method exhibit similar levels of precision, reinforcing the reliability of the approach. Conventional surveying instruments, which may include tools like total stations, laser scanners, or manual measuring devices, are known for their high accuracy, but they also tend to be more time-consuming, labor-intensive, and prone to human error during data collection. In contrast, the method depicted in Figure 4.2 shows that modern technologies or automated techniques can not only match the accuracy of these conventional instruments but can also streamline the process, making it more efficient. Both the traditional and the new method offer a relatively accurate representation of the ruts and potholes' dimensions and area, but the latter's added

advantages, such as reduced human error and faster data processing, make it an attractive alternative.

This suggests that the new method holds considerable potential for improving the precision and efficiency of rut and pothole measurement, providing a reliable solution for applications that require consistent and accurate monitoring of road conditions. Therefore, it can be concluded that both methods are equally capable of producing accurate measurements, but the newer method might offer additional benefits in terms of operational efficiency and practicality.

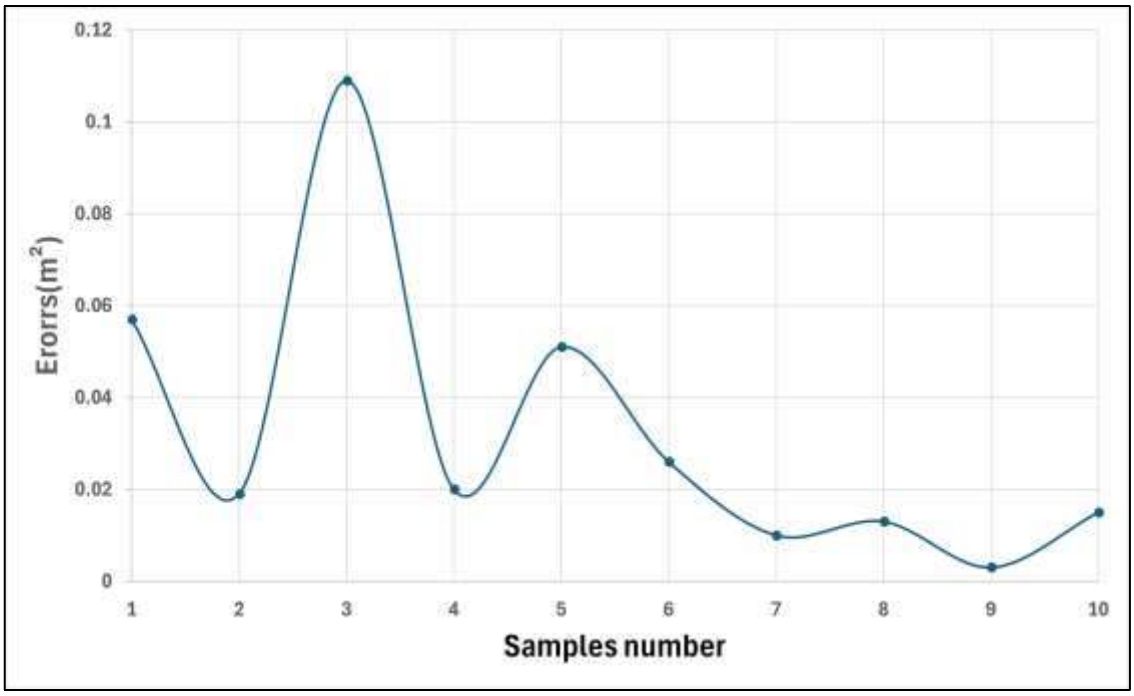


Figure 4.2: The Graph of The Difference Of The Area Errors Of Patches.

The accuracy of the approach that has been presented in differentiating between pavement surfaces that are cracked and those that are not cracked is shown in Figure 4.4. This method is capable of discriminating between the two types of surfaces with an amazing accuracy rate of up to 96 percent. The great degree of accuracy that this method provides allows for the thorough and dependable evaluation of the status of pavements. since a result, the technique is extremely beneficial for applications in pavement management and road maintenance, since it guarantees that sections that have deteriorated are accurately detected and remedied in a timely way.

In addition, the system is capable of identifying and categorizing fractures into a variety of different types, such as crocodile (alligator) cracking, longitudinal cracks, transverse cracks, and diagonal cracks. This categorization capacity is an important tool in evaluating the degree of degradation that has occurred and gaining a knowledge of the many types of stresses that the pavement has been subjected to throughout time. As a result, it is possible to obtain a clearer and more complete depiction of the condition of the pavement. Additionally, the precision of the approach in measuring the widths of cracks is around one centimeter, which is more than adequate for the purposes of conducting in-depth assessments of the severity of cracks and for forecasting the likelihood of future deterioration in the event that prompt assistance is not administered.

The approach provides useful insights into the severity and evolution of pavement deterioration by offering both crack-type categorization and precise crack-width measurements. The insights provided lend assistance to the process of making informed decisions on the necessity of repairs and contribute to the prioritization of maintenance activities on the basis of their urgency and the projected impact that they will have. In addition, the system offers assistance in the process of selecting the most appropriate means of rehabilitation, including surface treatments, patching, or more comprehensive rebuilding, in order to guarantee that strategies for maintenance are both cost-effective and effectively aimed to extend the life and performance of the pavement. In general, road management systems are able to gain considerable benefits from the capability of consistently detecting and quantifying cracks, which allows for interventions to be made in a timely manner in order to avoid additional degradation and to improve the long-term sustainability of the transportation infrastructure. Examples of fractured and uncracked surfaces that were seen before the automated identification process are provided in Figure 4.5.

In order to compare the environmental advantages of unmanned aerial vehicle (UAV)-based pavement inspections to those of traditional ground-vehicle inspections, a site-specific quantitative evaluation was carried out as part of the second portion of the research. In order to cover a distance of around fifty kilometers, a crew consisting of three cars is often required to carry out a standard inspection. The average fuel usage of each vehicle is around 15 liters for every inspection cycle, which amounts to about 10 liters of diesel for every 100 kilometers traveled. Taking into consideration that the combustion of diesel releases around

2.68 kilograms of carbon dioxide for every liter, the whole quantity of carbon dioxide emissions for a single inspection cycle comes to around 40.2 kilograms.

On the other hand, a single examination that utilizes unmanned aerial vehicles (UAVs) requires the use of around 0.5 kilowatt-hours of electrical energy. If we assume that the emission factor of the local energy system is 0.5 kilograms of CO_2 per kilowatt-hour, the total emissions per flight of an unmanned aerial vehicle (UAV) amount to around 0.25 kilograms of CO_2. This indicates a decrease in carbon emissions of more than 99 percent compared to the conventional vehicle-based inspection technique. The results of these research emphasize the tremendous environmental benefits that can be achieved via the use of unmanned aerial vehicle (UAV) technology for pavement inspections, showing that it has the ability to greatly decrease carbon emissions while at the same time ensuring that the accuracy and efficiency of inspections are maintained at a high level.

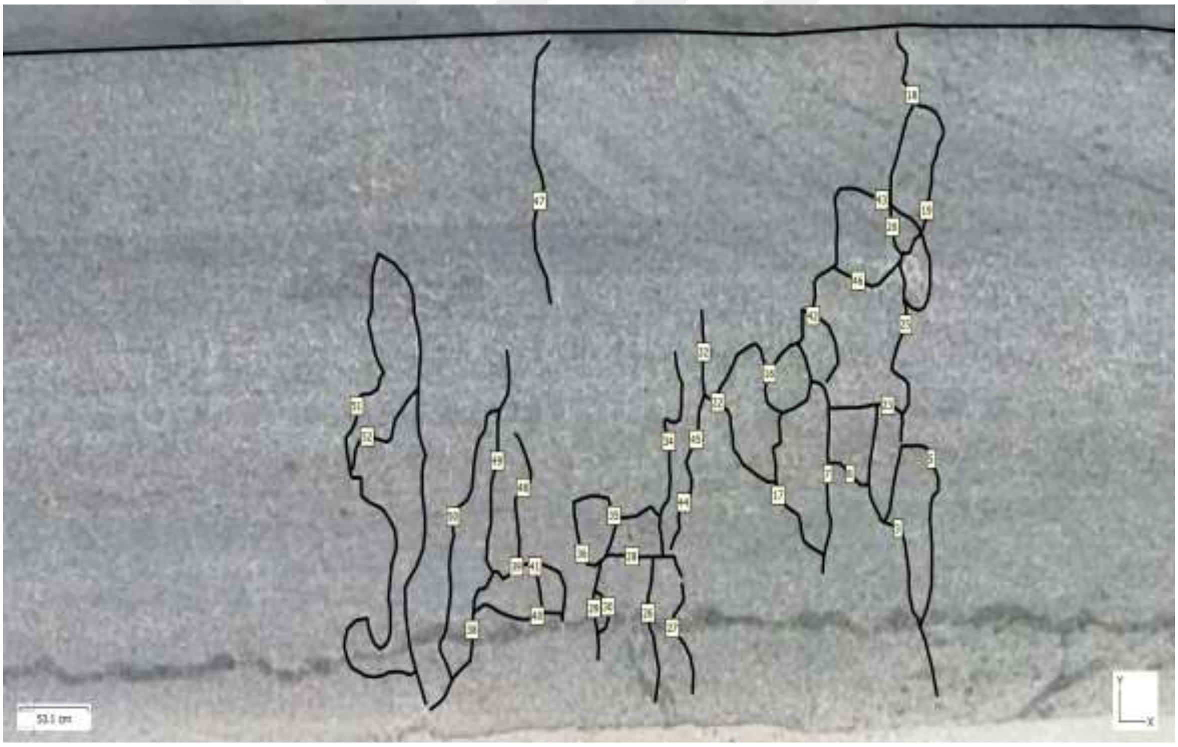


Figure 4.3: Sample Of The Crack Regions.

Figure 4.4: The Cracked and Uncracked Areas Before the Crack Mapping Process.

4.2 DISCUSSION

The results of this investigation show that by integrating unmanned aerial vehicle technology with ground control points, a significant improvement may be achieved in comparison to traditional pavement inspection techniques in terms of accuracy, efficiency, safety, and sustainability. This enhancement is of particular importance in urban settings, in which the minimization of traffic interruptions and the maintenance of the safety of field people are essential conditions. In the past, the examination of the pavement has relied extensively on manual measures and on-site review. This process normally necessitates the participation of a team composed of three to four personnel, two of whom are tasked with the physical measurements and two of whom are assigned to traffic management. Due to the fact that inspectors are positioned in close proximity to vehicles that are in motion, the safety issues that are associated with these types of field activities are not the only problems that they provide. In addition, they frequently require that partial or full lane closures be put in place, which leads to delays, traffic congestion, and general inconvenience for people who are using the route.

In contrast, the method of utilizing unmanned aerial vehicles for the purpose of inspection that is used in this research project makes the workflow of operations considerably more efficient. Because the procedure may be carried out by a single trained operator, it removes the requirement for a large number of people to be present on the ground. The reduction in labor that has been implemented in this case leads to an increase in safety by decreasing the likelihood of being exposed to roadside risks. At the same time, it results in a decrease in the expenses of operations. Unmanned aerial vehicles are able to capture high-resolution imagery across extensive pavement sections in a far shorter amount of time than manual inspections need. This capability allows for more regular and thorough surveillance of metropolitan road networks. Both Feitosa et al. [12] and Romero-Chambi et al. [9], both of whom stressed the efficiency and reliability of unmanned aerial vehicles for quick pavement condition evaluations, conducted research that produced results that are compatible with these findings.

The findings further suggest that the measurements that were obtained from the UAV exhibit a significant degree of accuracy. For instance, the root mean square error of the measurements of rut depth that were obtained in this study came to 3.54 millimeters, which is in good agreement with the results that were obtained by Tan and Li [11]. The latter researchers found accuracies of about one centimeter when employing unmanned aerial vehicle photogrammetry. The capability of unmanned aerial vehicle images, when used in conjunction with ground control points, to identify minor pavement distresses that would otherwise necessitate the use of physical equipment for measurement is validated by this degree of precision. In a similar manner, the detection and classification of cracks with a precision of around one centimeter supports the research conducted by Nappo and colleagues [68]. This study found that unmanned aerial vehicles have the capacity to distinguish between longitudinal, transverse, and crocodile cracks with a high degree of reliability. Proactive pavement management is dependent on the identification of cracks in such a precise manner, which allows maintenance crews to take action before structural failures become more severe.

The patch area measurements, which had a root mean square error of 4.44 cm2, were likewise found to be accurate and in line with the values that were published in other investigations. That being said, when the findings were compared to the results of Silva et al. [14], who produced somewhat lower RMSE values, there were minor differences noted. These disparities can be ascribed to variations in the types of the unmanned aerial vehicles, the resolution of the cameras, the weather circumstances, or the reflectivity of the surface that was present at the time of data acquisition. Nonetheless, the total accuracy attained in this study continues to be within an acceptable range for actual pavement inspection needs, which reaffirms the resilience of the proposed UAV-based technique.

In addition to its high level of precision and operating efficiency, the environmental effect that the unmanned aerial vehicle approach has is one of its most significant benefits. Due to the fact that traditional inspections usually need the use of numerous cars in order to transfer workers and equipment, the process is accompanied by fuel consumption, noise, and carbon dioxide emissions that are measurable in nature. According to the analysis that was carried out in this study, the amount of carbon dioxide that is generated by a typical inspection route of 50 kilometers utilizing three ground vehicles is roughly 40.2 kg. In comparison, the amount of carbon dioxide that is generated by a single flight of an unmanned aerial vehicle is just 0.25 kilograms, which equates to a reduction in emissions of more than 99%. When unmanned aerial vehicles were used in place of traditional inspection fleets, Santos et al. [19] and Aurangzeb et al. [20] discovered reductions of up to ninety percent. Their findings were comparable to those that were previously published. Because it is so closely in line with the aims of global sustainability and because it emphasizes the significance of unmanned aerial vehicles as a crucial technical component of systems that are employed to monitor infrastructure in an ecologically responsible manner, this highly noticeable decrease in carbon footprint is of great importance.

The significance of these discoveries is not limited to the advantages they provide in the short term. Unmanned Aerial Vehicles are capable of gathering standardized, repeatable picture data, which allows for the creation of predictive maintenance models. This shift from reactive to proactive pavement management has the potential to dramatically lower the costs associated with maintenance during the life cycle of the pavement, in addition to enhancing road safety by addressing issues before they reach a critical stage. The integration of data that has been collected from unmanned aerial vehicles with the use of sophisticated artificial intelligence and deep learning algorithms provides a future path that is revolutionary in nature. Models of this kind would have the capability of automating the detection, categorization, and quantification of distresses in pavements. This would result in an increase in scalability and a decrease in the dependence on manual interpretation.

The current research concentrated on an urban corridor that had relatively little traffic, but the approach of unmanned aerial vehicles and ground control points (UAV-GCP) demonstrates that it has significant potential for implementation in environments that are more complicated, such as those that are characterized by heavy traffic and numerous structural barriers. In order to implement this in environments such as these, it would be necessary to coordinate with local authorities in order to handle issues of regulation, operation, and safety. In order to successfully integrate the technology, it will be essential to schedule flights during times of low demand and to make sure that all local unmanned aerial vehicle rules are being followed. The necessity for coordination that is demonstrated here is in agreement with the findings of Romero-Chambi et al. [7]. In their research, the aforementioned authors emphasize the importance of institutional collaboration as a crucial element in the process of incorporating unmanned aerial vehicle inspections into plans for municipal infrastructure.

The precise selection, placement, and distribution of GCPs are necessary for the accomplishment of high precision and dependability while conducting unmanned aerial vehicle (UAV)-based inspections. To prevent mistakes from being caused by reflections or inadequate visibility, it is necessary to take into account variables such as patterns of shadows, possible occlusions, and the angle of the sun while determining their placing. In the same way, environmental parameters like as the speed of the wind, the quality of the light, and the conditions of the atmosphere are of the utmost importance when it comes to the clarity of the image and the accuracy of photogrammetric reconstruction. Performing flights within the most favorable circumstances (cloudless sky, steady illumination, no wind) assists in minimizing picture distortion and increases the accuracy of the ultimate three-dimensional models. These factors are necessary in order to reduce the potential for measurement bias and to guarantee that the data that is used for making decisions is dependable.

The results of this investigation demonstrate that unmanned aerial vehicle ground control point (UAV-GCP) photogrammetry is a practical, accurate, and sustainable option that may be used as a substitute for conventional pavement inspection methods. In addition to providing significant advantages in terms of safety, resource efficiency, and environmental performance, the approach not only increases the accuracy of pavement distress detection and quantification but also provides other benefits. The results obtained provide a foundation for the development of new technology in the future, namely in the areas of pavement management systems that are based on the cloud, artificial intelligence-driven fault identification, and the operation of unmanned aerial vehicles that are autonomous. Unmanned Aerial Vehicle technology has the potential to play a transformational role in the intelligent and sustainable management of transportation infrastructure. However, in order to realize this potential, it is necessary to continue developing the technology and to establish appropriate legal frameworks.

Recent advances in asphalt mixture modification have demonstrated substantial improvements in pavement performance, particularly in resistance to rutting, moisture damage, and permanent deformation. Saedi and ORUÇ [80] investigated the incorporation of nano-bentonite and fatty arbocel in warm mix asphalt and reported notable enhancements in moisture resistance and rutting performance. Their findings indicate that material-level improvements play a critical role in extending pavement service life, especially under adverse environmental and loading conditions. Such improvements emphasize the need for accurate and reliable inspection techniques capable of detecting early-stage surface distresses to support timely maintenance decisions.

Saedi and Oruc [81] investigated the impact of SBS polymer, viatop premium, and fiber-reinforced polymers (FRP) on the performance of stone mastic asphalt. Their research demonstrated that these modifiers substantially enhance mechanical stability and resistance to deformation, especially under substantial traffic loads. These findings underscore the necessity of monitoring pavement surface conditions to evaluate the performance of modified asphalt mixtures in practical scenarios. The UAV-based inspection methods described in this work effectively capture high-resolution surface data, facilitating exact assessment of rutting and surface distress progression over time.

Subsequent investigation by Saedi et al. [82] examined the synergistic impact of SBS and proplast additives on stone mastic asphalt composites. The research determined that the combined use of these modifiers significantly diminishes permanent deformation and improves durability. These findings underscore the imperative for sophisticated inspection technologies that can measure minute surface alterations with precision. The UAV–GCP methodology utilized in this research provides an effective approach for documenting surface differences, facilitating performance-based pavement assessment.

Recent research by Saedi [83] assessed the impact of para-aramid and micro-polyolefin fibers on permanent displacement in stone mastic asphalt. The findings validated that fiber reinforcing significantly restricts the advancement of rut depth under cyclic loading. Precise assessment of rut depth is crucial for evaluating the enduring advantages of these improvements. The minimal RMSE values obtained in the present UAV-based measurements indicate the appropriateness of this method for monitoring deformation in fiber-reinforced pavements.

Furthermore, Saedi [84] examined the influence of de-icing agents on moisture susceptibility in hot mix asphalt incorporating biomass fibers. The research shown that fiber-modified mixes show enhanced resilience to moisture-related deterioration in severe weather conditions. This emphasizes the necessity of ongoing and unobtrusive pavement monitoring devices, especially in areas subjected to extreme weather conditions. UAV-based inspections provide a secure and effective substitute for conventional methods, enabling regular evaluations without obstructing traffic.

5. CONCLUSION AND FUTURE WORKS

5.1 CONCLUSION

In conclusion, this study provides a comprehensive evaluation of the integration of Unmanned Aerial Vehicles (UAVs) and Ground Control Points (GCPs) in the inspection of flexible pavement systems, with particular focus on the detection and quantification of surface distresses such as rutting, patching, and cracking. Through rigorous experimental design and data analysis, the results of this research validate the technical feasibility and operational advantages of using UAV-based systems, enhanced with GCPs, in achieving high spatial accuracy and repeatability in pavement surface assessments. Specifically, the system achieved a rut depth measurement accuracy within ±3 mm , patch area detection within ±2.44 cm^2 and an accuracy of up to 96% in identifying cracked and non-cracked areas and the type of cracks, metrics that are not only comparable to those derived from traditional manual inspection methods, but in many aspects, surpass them in precision and efficiency.

The findings have significant implications for modern road maintenance practices, particularly in light of the growing global emphasis on intelligent infrastructure and smart transportation systems. The implementation of UAVs for pavement monitoring represents a marked shift toward automation and digitization within the field of civil engineering. With the use of GCPs, georeferencing errors are minimized, ensuring that the resulting 3D reconstructions and orthomosaics are aligned with actual site coordinates. This enhanced accuracy facilitates better decision-making in maintenance planning, budgeting, and prioritization, particularly in extensive road networks where conventional ground surveys would be time-consuming, labor-intensive, and costly.

The incorporation of UAVs into the pavement inspection workflow presents numerous advantages:

a. The method offers cost-efficiency by reducing the need for large field crews, specialized vehicles, or lane closures factors that traditionally escalate the financial and logistical burdens of roadway inspections.

b. UAVs provide rapid data acquisition over large or inaccessible areas, making them especially valuable in high-traffic urban settings or remote regions where traditional surveying is impractical or unsafe.

c. The aerial perspective enables the early detection of surface anomalies, allowing for proactive maintenance and reducing the risk of more severe structural failures.

The addition of GCPs further enhances the reliability of UAV-collected data by improving spatial referencing, which is essential for long-term pavement monitoring, comparative studies, and integration with GIS systems. This is particularly important when longitudinal studies are conducted over multiple years, as slight misalignments in datasets can result in erroneous interpretations of pavement deterioration rates.

Furthermore, UAV systems contribute to increased safety for personnel by minimizing the need for field inspectors to work in active traffic environments. This reduction in occupational risk is a notable benefit, especially in regions with high accident rates among roadside workers.

5.2 LIMITATIONS AND CHALLENGES

Despite these advantages, several limitations must be acknowledged. One significant challenge is the dependence on favorable weather conditions; UAV flights are generally not feasible in high winds, heavy precipitation, or low-visibility environments. This constraint can limit the applicability of UAVs in regions with unpredictable or extreme weather patterns, where inspections must occur regardless of conditions.

Another challenge is the regulatory landscape surrounding drone operations. In many jurisdictions, UAV deployment for civil engineering purposes requires special licenses, airspace permissions, and adherence to strict operational guidelines—factors that can delay or complicate fieldwork. In addition, the deployment of GCPs still requires some degree of manual labor and field access, which could offset the full automation benefits promised by UAVs, especially in highly urbanized or restricted-access zones.

There are also technical limitations regarding payload capacity, battery life, and sensor resolution, which can constrain mission duration and the level of detail captured in high-traffic or complex urban environments. Moreover, the initial investment in equipment, training, and software (e.g., photogrammetry tools like Agisoft Metashape) may be a barrier for smaller agencies or municipalities with limited budgets.

5.3 RECOMMENDATIONS AND FUTURE WORK

Future studies should focus on overcoming these regulatory barriers and exploring how environmental factors of affect image quality and inspection accuracy such as traffic congestion. Additionally, future research should focus on evaluating the impact of using ground control points on the accuracy of the extracted 3D model at different flight altitudes. Also, study the use of ground control points and algorithms together in the image processing used to obtain the 3D model.

Based on the outcomes of this study, it is recommended that transportation agencies and infrastructure management authorities consider integrating UAV-GCP systems into their regular inspection and maintenance workflows. Emphasis should be placed on developing standardized protocols for UAV data acquisition, GCP deployment, and AI-based post-processing to ensure consistency and reliability across projects and regions.

Future research should explore the integration of artificial intelligence (AI) and machine learning models with UAV-GCP-acquired datasets to automate the detection and classification of pavement distress. This would further reduce reliance on manual interpretation and enhance real-time decision-making. Additionally, studies involving multi-sensor UAV platforms incorporating thermal, LIDAR, or hyperspectral imaging may provide deeper insights into subsurface conditions, expanding the utility of UAV systems beyond surface-level analysis.Additionally, future research should focus on evaluating the impact of using ground control points on the accuracy of the extracted 3D model at different flight altitudes.

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APPENDIX

AGISOFT METASHAPE PROCESSING REPORT

Agisoft Metashape

Processing Report
07 August 2024