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Enhancing Road Infrastructure Monitoring: Integrating Drones for Weather-Aware Pothole Detection

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Abstract:

The abstract outlines the research proposal focused on the utilization of Unmanned Aerial Vehicles (UAVs) for monitoring potholes in road infrastructure affected by various weather conditions. The study aims to investigate how different materials used to fill potholes, such as water, grass, sand, and snow-ice, are impacted by seasonal weather changes, ultimately affecting the performance of pavement structures. By integrating weather-aware monitoring techniques, the research seeks to enhance the rigidity and resilience of road surfaces, thereby contributing to more effective pavement management systems. The proposed methodology involves UAV image-based monitoring combined with advanced super-resolution algorithms to improve image refinement, particularly at high flight altitudes. Through case studies and experimental analysis, the study aims to assess the geometric precision of 3D models generated from aerial images, with a specific focus on road pavement distress monitoring. Overall, the research aims to address the challenges of traditional road failure detection methods by exploring cost-effective 3D detection techniques using UAV technology, thereby ensuring safer roadways for all users.

Keywords: Highlighting prominent keywords relevant to the thesis, such as drones, Unmanned Aerial Vehicles (UAVs),Pothole Detection, Road Infrastructure Monitoring, Weather-Aware Monitoring, Pavement Management Systems, Super-Resolution Algorithms, Geometric Precision 3D Modeling, Road Pavement Distress, Image Refinement.

List of Abbreviations:

AP	Average Precision
ANN	Artificial Neural Network
AI	Artificial Intelligence
CS	Cycle Spinning
CNNs	Convolutional Neural Networks
DWT	Discrete Wavelet Transforms
DT-CWT	Dual Tree Complex Wavelet Transform
DEM	Digital Elevation Models
ET	Evapotranspiration
GPS	Global Positioning System
GAN	Generative Adversarial Networks
GFF	Global Feature Fusion
GPR	Ground Penetrating Radar
GCPs	Ground Control Points
GNSS	Global Navigation Satellite Systems
HR	High Resolution
HMA	Hot Mix Asphalt
INS	Initial Navigation Systems
ISC	Inter Subband Correlation Technique
IOT	Internet Of Things
IMUs	Inertial Measurement Units
LR	Low-Resolution
LiPo	Lithium–Polymer
LiDAR	Light Detection And Ranging
MST	Minimum Spanning Tree
MLS	Mobile Laser Scanning
MSE	Mean Square Error
MAP	Mean Average Precision
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
ML	Machine Learning
OD	Object Detection
PDS	Pothole Detection System
PA	Porous Asphalt
PCA	Principal Component Analysis
RFDM	Residual Feature Distillation Mechanism

RMSD	Root Mean Square Deviation
RNN	Recurrent Neural Network
RMS	Road Management System
RMSE	Root Mean Square Error
RPi	RaspberryPi
SVM	Support Vector Machine
SR	Super-Resolution
SDK	Software Development Kit
SAR	Synthetic Aperture Radar
SHM	Structural Health Monitoring
SA	Spatial Attention
SISR	Single Image Super Resolution
SWT	Stationary Wavelet Transform
TLS	Terrestrial Laser Scanner
UAV	Unmanned Aerial Vehicle
VVIR-PDE	Vector-Valued Image Regularization with Partial Differential Equations
WZP	wavelet zero padding
WHO	World Health Organization
YOLO	You Only Look Once

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Chapter 1
Introduction

1.1 Background and Context

Road infrastructure is crucial for the functioning of modern societies, facilitating economic activities, social interactions, and regional connectivity (Parsons et al., 2018). However, maintaining roads in optimal condition is a multifaceted challenge, influenced by factors such as traffic loads, adverse weather conditions, limited resources, and technological advancements (Qu et al., 2018). Potholes, in particular, pose a significant problem on roadways globally, arising from the combined effects of traffic wear, moisture ingress, and freeze-thaw cycles (Pintér & Nagy, 2021).

Detecting and repairing potholes promptly is paramount for preventing accidents, minimizing vehicle damage, and preserving road safety (da Rosa et al., 2020). Despite efforts to address this issue, traditional methods of pothole detection and repair often prove inadequate due to their reliance on manual inspection and reactive maintenance approaches (Madokoro et al., 2021). Furthermore, the increasing demand for efficient transportation infrastructure necessitates innovative solutions that can enhance the effectiveness and sustainability of road maintenance practices (Parsons et al., 2018).

In recent years, advancements in technology, particularly the emergence of unmanned aerial vehicles (UAVs) and machine learning algorithms, have offered new opportunities for road infrastructure monitoring and maintenance (Brown et al., 2019). UAVs equipped with high-resolution cameras and LiDAR sensors can efficiently capture detailed images and data of road surfaces, enabling the automated detection of potholes and other defects (Zhang et al., 2019).

This integration of drones and advanced analytics not only improves the accuracy and efficiency of pothole detection but also enables proactive maintenance strategies that prioritize repairs based on real-time data analysis (da Rosa et al., 2020). Moreover, leveraging UAVs for road infrastructure monitoring reduces the safety risks associated with manual inspections and enhances the overall cost-effectiveness of maintenance operations (Pintér & Nagy, 2021).

By harnessing the capabilities of UAVs and machine learning technologies, transportation agencies and infrastructure managers can enhance the resilience, safety, and sustainability of road networks, ultimately contributing to the efficient functioning of societies and the well-being of communities (Madokoro et al., 2021).

1.1.1 Importance of Road Infrastructure

Road infrastructure serves as a cornerstone of modern society, facilitating economic growth, social cohesion, regional development, and environmental sustainability. This section delves into the importance of road infrastructure across various dimensions, including its economic impact, role in social connectivity, contribution to regional development, and promotion of environmental sustainability.

1. **Economic Impact**

Efficient road networks are vital for fostering economic development and facilitating trade and commerce. By providing connectivity between production centers, markets, and consumers, well-maintained roads reduce transportation costs, enhance supply chain efficiency, and improve the competitiveness of businesses (Parsons et al., 2018). Moreover, roads serve as conduits for the movement of goods, enabling industries to access raw materials, distribute products, and reach customers efficiently. Investments in road infrastructure not only stimulate economic activity but also generate employment opportunities and spur local development.

2. **Social Connectivity**

Roads play a crucial role in fostering social interactions, promoting cultural exchange, and enhancing community cohesion. By connecting communities, neighbourhoods, and regions, roads facilitate access to essential services such as education, healthcare, employment opportunities, and recreational facilities (Da Rosa et al., 2020). Additionally, roads enable individuals to participate in social and cultural activities, visit family and friends, and engage in community events. During emergencies, such as natural disasters, roads serve as lifelines for the swift mobilization of emergency responders, evacuation of residents, and distribution of relief supplies.

3. **Regional Development**

Investments in road infrastructure are instrumental in promoting regional development and reducing disparities between urban and rural areas. Improved road connectivity enhances market access for agricultural products, facilitates tourism development, and attracts businesses to previously underserved regions (Pintér & Nagy, 2018). By providing access to markets, employment opportunities, and social services, roads stimulate economic growth, alleviate poverty, and improve living standards in rural communities. Furthermore, road infrastructure projects create employment opportunities, stimulate local economies, and catalyze sustainable development in both developed and developing regions.

4. Environmental Sustainability

Sustainable road infrastructure plays a crucial role in promoting environmentally friendly transportation modes and mitigating the environmental impact of transportation activities (Qu et al., 2018). By encouraging the use of public transit, cycling, and walking, sustainable road infrastructure reduces reliance on private vehicles, alleviates traffic congestion, and decreases greenhouse gas emissions. Green road design practices, such as the use of recycled materials, energy-efficient lighting, and stormwater management systems, minimize environmental degradation and enhance the resilience of road networks to climate change. Additionally, investments in sustainable transportation infrastructure contribute to efforts to achieve carbon neutrality targets, improve air quality, and create healthier and more liveable communities.

In summary, road infrastructure plays a pivotal role in supporting economic growth, enhancing social connectivity, promoting regional development, and advancing environmental sustainability. Recognizing the multifaceted importance of road infrastructure underscores the need for strategic investments, efficient maintenance practices, and sustainable development strategies to ensure the continued well-being and prosperity of societies.

1.1.2 Challenges in Road Maintenance

Maintaining road infrastructure in optimal condition is essential for ensuring safe and efficient transportation systems. However, transportation authorities and infrastructure managers face numerous challenges in addressing the ongoing deterioration of roads. These challenges arise from factors such as traffic loads, adverse weather conditions, limited funding, inefficient maintenance practices, and environmental concerns. Understanding and effectively addressing these challenges are critical for preserving road infrastructure and ensuring the safety and well-being of communities.

1. Deterioration from Traffic Loads

Continuous vehicle traffic imposes significant stress on road surfaces, leading to wear and tear over time. High-traffic corridors, including highways and urban streets, are particularly susceptible to pavement distress such as cracks, potholes, and rutting. The cumulative effect of heavy vehicle loads and frequent use accelerates pavement degradation, compromising road safety and performance. Left untreated, pavement distress can escalate into more severe structural issues, necessitating costly repairs and reconstruction efforts.

2. Adverse Weather Conditions

Extreme weather events, such as heavy rainfall, snowfall, temperature fluctuations, and freeze-thaw cycles, exacerbate the deterioration of road surfaces and pavement structures. Rainwater infiltration, frost action, and thermal expansion and contraction contribute to the erosion of road materials, weakening pavement integrity, and leading to surface failures. Regions with harsh climates, including northern latitudes or mountainous areas, face additional challenges in maintaining road infrastructure due to prolonged exposure to severe weather conditions.

3. Limited Funding

Insufficient funding poses a significant barrier to effective road maintenance and infrastructure investment. Budget constraints often force transportation agencies to prioritize critical repairs over routine maintenance activities, leading to deferred maintenance and increased infrastructure backlog. Fluctuations in government funding, competing budgetary priorities, and political considerations further complicate long-term planning and resource allocation for road maintenance projects. Limited funding also hampers investments in innovative maintenance technologies, research and development initiatives, and capacity-building programs, constraining the ability of transportation agencies to address emerging challenges and future infrastructure needs.

4. Inefficient Maintenance Practices

Inadequate planning, resource allocation, and execution of maintenance activities contribute to inefficiencies in road maintenance operations. Poor coordination between various stakeholders, including government agencies, contractors, and utility companies, leads to delays, cost overruns, and disruptions in project delivery. The absence of standardized maintenance protocols, performance metrics, and quality assurance mechanisms makes it difficult to assess the effectiveness of maintenance interventions and ensure consistent service delivery. Lack of skilled personnel, outdated equipment, and reliance on traditional maintenance methods further impede the efficiency and effectiveness of road maintenance operations.

5. Environmental Concerns

Road maintenance activities have environmental implications, including energy consumption, resource depletion, and pollution generation. Asphalt production, for instance, emits greenhouse gasses and other pollutants, contributing to air and water pollution and exacerbating climate change. Improper disposal of construction materials, waste runoff, and habitat fragmentation can degrade ecosystems, harm wildlife, and compromise biodiversity conservation efforts. Sustainable road maintenance practices, such as using recycled materials, implementing erosion control measures, and minimizing environmental disturbances, are essential for mitigating environmental impacts and promoting ecological sustainability.

In response to these challenges, transportation authorities and infrastructure managers must adopt innovative strategies and technologies to optimize resource allocation, improve operational efficiency, and ensure the long-term sustainability of road infrastructure. This may include leveraging data-driven decision-making, embracing sustainable practices, fostering collaboration with stakeholders, and exploring alternative financing mechanisms. By addressing the root causes of road maintenance challenges and implementing proactive measures, societies can preserve the integrity of road infrastructure, promote economic prosperity, and enhance the quality of life for current and future generations.

1.2 Significance of Road Infrastructure Monitoring

Road infrastructure monitoring serves as a cornerstone in ensuring the safety, reliability, and longevity of transportation networks. Through systematic assessment of road conditions and identification of potential hazards, monitoring programs empower transportation agencies to prioritize maintenance interventions, allocate resources effectively, and enhance the overall performance of road networks (Madokoro, Kiguchi, Nagayoshi, Chiba, Inoue, Chiyonobu, & Sato, 2021; Pintér & Nagy; Parsons, Bratanov, Gaston, & Gonzalez, 2018; da Rosa, Wehrmeister, Brito, Lima, & Pereira, 2020; Qu, Huang, & Zhang, 2018). In this section, we will delve into the critical importance of road infrastructure monitoring, highlighting both the significance of early detection of potholes and the indispensable role of monitoring in ensuring road safety.

1.2.1 Importance of Early Detection of Potholes

Potholes, characterized by localized surface disruptions, present significant safety risks and economic burdens for road users and transportation agencies alike (Pintér & Nagy; Madokoro, Kiguchi, Nagayoshi, Chiba, Inoue, Chiyonobu, & Sato, 2021). These defects typically arise from a combination of factors, including traffic loads, weather fluctuations, and inadequate pavement maintenance. While small potholes may initially seem inconsequential, they have the potential to escalate into larger defects, exacerbating vehicle damage, traffic congestion, and safety hazards.

1. **Safety Risks:**

Potholes pose immediate safety hazards for motorists, cyclists, and pedestrians by causing sudden jolts, loss of vehicle control, and accidents (Nguyen et al., 2018). Vehicles traversing pothole-ridden roads are at risk of tire blowouts, suspension damage, and wheel misalignment, leading to vehicle breakdowns and collisions. Additionally, potholes may obscure road markings, traffic signs, and pedestrian crossings, heightening the risk of accidents, particularly during adverse weather conditions or low-light scenarios.

2. **Economic Costs:**

In addition to safety concerns, potholes impose substantial economic costs on road users and transportation agencies (Parsons, Bratanov, Gaston, & Gonzalez, 2018). Vehicle repairs, including tire replacements, wheel alignments, and suspension repairs, can incur significant expenses for motorists, impacting household budgets and reducing disposable income. Moreover, pothole-related accidents result in property damage, medical expenses, and insurance claims, further straining individuals' finances and burdening insurance providers.

3. **Traffic Congestion:**

Pothole-ridden roads often experience heightened congestion as motorists slow down or swerve to avoid surface irregularities, leading to traffic bottlenecks and delays (Qu, Huang, & Zhang, 2018). Congested roadways reduce travel speeds, increase travel times, and diminish overall road capacity, resulting in productivity losses for businesses, commuters, and freight carriers. Furthermore, traffic congestion exacerbates air pollution, fuel consumption, and greenhouse gas emissions, contributing to environmental degradation and public health concerns.

4. **Infrastructure Damage:**

Potholes not only inflict damage on vehicles but also compromise the underlying road infrastructure, necessitating costly repairs and rehabilitation efforts (da Rosa, Wehrmeister, Brito, Lima, & Pereira, 2020). As potholes expand over time, they compromise pavement integrity, weaken subgrade support, and accelerate pavement deterioration, necessitating more extensive and expensive rehabilitation projects. Additionally, potholes may exacerbate stormwater runoff and erosion, compromising roadside drainage systems and leading to localized flooding and soil erosion.

5. **Public Perception:**

The presence of potholes reflects poorly on the overall quality and maintenance of road infrastructure, influencing public perception, satisfaction, and trust in transportation agencies and government authorities (Pintér & Nagy; Madokoro, Kiguchi, Nagayoshi, Chiba, Inoue, Chiyonobu, & Sato, 2021). Pothole-ridden roads convey a sense of neglect, inefficiency, and disrepair, eroding public confidence in infrastructure investments, taxation policies, and government accountability. Furthermore, potholes may dissuade potential investors, businesses, and tourists from relocating or investing in areas with poor road conditions, hindering economic development and regional competitiveness.

In conclusion, early detection of potholes is paramount for mitigating safety risks, minimizing economic costs, reducing traffic congestion, preserving infrastructure integrity, and maintaining public trust in transportation agencies. Through proactive monitoring and timely intervention, transportation authorities can safeguard road users, optimize resource allocation, and uphold the reliability and performance of transportation networks. By investing in robust monitoring systems and embracing data-driven approaches, societies can build safer, more resilient, and more sustainable transportation infrastructure for the benefit of all.

1.2.2 Role of Monitoring in Ensuring Road Safety

Effective monitoring of road conditions is paramount for identifying potential hazards, prioritizing maintenance activities, and mitigating safety risks (Madokoro et al., 2021). Through systematic data collection and analysis, transportation agencies can proactively address emerging issues, implement preventive measures, and optimize resource allocation strategies. In this section, we will explore the multifaceted role of monitoring in ensuring road safety, emphasizing its contributions to accident prevention, hazard identification, infrastructure management, public engagement, and continuous improvement.

1. **Accident Prevention:** One of the primary objectives of road infrastructure monitoring is

to prevent accidents and minimize associated human and economic costs (Li et al., 2021). By systematically assessing road conditions, identifying accident-prone locations, and implementing targeted safety improvements, transportation agencies can reduce the likelihood of collisions, injuries, and fatalities. Monitoring programs often rely on historical accident data, traffic flow analyses, and predictive modelling techniques to identify high-risk areas and prioritize safety interventions, such as signage upgrades, intersection improvements, and roadway realignments.

2. **Hazard Identification:** Monitoring programs play a crucial role in identifying potential safety hazards and mitigating risks before they escalate into accidents or emergencies (Rafey et al., 2023). Through regular inspections, data collection, and analysis, transportation agencies can detect a wide range of hazards, including pavement defects, geometric deficiencies, and roadside obstructions. By proactively addressing these hazards through maintenance activities, signage enhancements, and targeted enforcement efforts, agencies can minimize the likelihood of accidents and improve overall road safety.
3. **Infrastructure Management:** Effective monitoring is essential for managing and maintaining the integrity of road infrastructure assets, including pavements, bridges, and signage systems (Klosterman & Richardson, 2017). By monitoring pavement conditions, structural health, and asset performance, transportation agencies can identify maintenance needs, prioritize investments, and extend the service life of critical infrastructure components. Monitoring programs often leverage advanced technologies, such as remote sensing, Geographic Information Systems (GIS), and pavement management systems, to collect, analyze, and visualize data for informed decision-making.
4. **Data-Driven Decision-Making:** Modern monitoring programs rely on data-driven approaches to inform decision-making and resource allocation (Ortega-Terol et al., 2017). By collecting and analyzing vast amounts of data on road conditions, traffic patterns, and infrastructure performance, transportation agencies can identify trends, patterns, and emerging issues that require attention. Data-driven decision-making enables agencies to allocate resources more efficiently, optimize maintenance schedules, and prioritize investments based on risk, cost-effectiveness, and strategic objectives.
5. **Public Engagement and Accountability:** Transparent and proactive monitoring practices promote public engagement, accountability, and trust in transportation agencies and government authorities (Parsons et al., 2018). By openly sharing data, reports, and performance metrics with stakeholders, agencies demonstrate their commitment to transparency, responsiveness, and continuous improvement. Public engagement

initiatives, such as community forums, feedback mechanisms, and citizen reporting platforms, empower residents to voice concerns, provide input, and participate in decision-making processes related to road safety and infrastructure management.

6. **Continuous Improvement:** Monitoring programs facilitate continuous improvement by enabling agencies to track performance metrics, evaluate the effectiveness of interventions, and adapt strategies based on feedback and lessons learned (Pintér & Nagy, n.d.). Through regular performance monitoring and evaluation, agencies can identify areas for improvement, refine strategies, and implement best practices to enhance road safety and infrastructure management. Continuous improvement fosters a culture of innovation, learning, and collaboration, ensuring that transportation agencies remain responsive to evolving challenges and emerging opportunities in the field of road safety and infrastructure management.

In conclusion, effective monitoring of road conditions is essential for ensuring the safety, reliability, and sustainability of transportation networks. By leveraging advanced technologies, data-driven approaches, and proactive strategies, transportation agencies can minimize safety risks, optimize resource allocation, and enhance public trust and engagement. Through continuous improvement and collaboration with stakeholders, agencies can build safer, more resilient, and more sustainable transportation infrastructure for the benefit of all.

1.3 Objective of the Study

1.3.1 Main Objective: Integration of Drones for Pothole Detection

The primary objective of this study is to explore and evaluate the integration of Unmanned Aerial Vehicles (UAVs), commonly known as drones, for pothole detection in road infrastructure (Li et al., 2019). This objective arises from the acknowledgment of the immense potential of UAV technology to revolutionize conventional methods of road inspection and maintenance (Roggero & Diara, 2024). By leveraging drones equipped with advanced imaging systems, including high-resolution cameras and LiDAR sensors, the overarching goal is to develop a more efficient, accurate, and cost-effective approach to detecting and monitoring potholes on road networks (Roggero & Diara, 2024).

The integration of drones into the pothole detection process offers several advantages over conventional ground-based methods (Li et al., 2019). Firstly, UAVs provide a distinctive vantage point to capture aerial imagery of road surfaces, enabling comprehensive coverage and detailed analysis of large areas within a relatively short time frame (Kong et al., 2017). This aerial perspective empowers transportation agencies and infrastructure managers to identify potholes with enhanced precision and detect early signs of deterioration not readily visible from ground level (Kong et al., 2017). Additionally, drones equipped with LiDAR technology can generate highly accurate 3D models of road surfaces, facilitating sophisticated analyses of pavement condition and geometry (Rivas Casado et al., 2017).

Moreover, the integration of drones for pothole detection holds the potential to significantly improve the overall safety and efficiency of road maintenance operations (Ribeiro-Gomes et al., 2017). By automating data collection and analysis, UAVs mitigate the need for manual inspections conducted by maintenance crews, thereby reducing exposure to hazardous working conditions and labor costs (Ribeiro-Gomes et al., 2017). Furthermore, timely identification of potholes and pavement defects enables proactive maintenance interventions, preventing damage escalation and mitigating the risk of accidents and vehicle damage (Zhou et al., 2017).

However, realizing the full potential of drone-based pothole detection requires addressing various technical, operational, and regulatory challenges (Suomalainen et al., 2018). These include optimizing flight planning and navigation algorithms to ensure adequate coverage and data collection accuracy, developing robust image processing and machine learning algorithms capable of reliably identifying and classifying potholes from aerial imagery, and navigating the regulatory landscape governing UAV operation in urban environments (Suomalainen et al., 2018).

1.3.2 Sub-objectives: Investigating Weather Influence, Assessing Detection Accuracy

In addition to the primary objective of integrating drones for pothole detection, this study incorporates two sub-objectives aimed at further enhancing the effectiveness and reliability of the detection process.

1. **Investigating Weather Influence:**

The first sub-objective delves into understanding the impact of weather conditions on the performance of drone-based pothole detection systems. Adverse weather phenomena, such as rain, snow, fog, and low light conditions, can significantly hinder data collection and analysis, affecting the visibility and quality of aerial imagery captured by UAVs (Torres-Rua, 2017).

To address this challenge, systematic experiments and analyses will be conducted under various weather scenarios. By simulating different weather conditions and assessing their effects on detection accuracy, this study aims to identify key environmental factors that influence performance. Additionally, strategies will be developed to mitigate the impact of adverse weather on detection systems. These strategies may include integrating weather forecasting data into flight planning algorithms, optimizing sensor configurations to enhance visibility, and adapting machine learning models to account for variations in image quality (Roggero & Diara, 2024).

Understanding the influence of weather conditions on pothole detection accuracy is crucial for developing robust and weather-resistant detection systems. By addressing this sub-objective, the study aims to enhance the reliability and applicability of drone-based pothole detection technologies across diverse environmental conditions.

2. **Assessing Detection Accuracy:**

The second sub-objective focuses on evaluating the accuracy and reliability of pothole detection algorithms deployed on UAV platforms. While drone-based imaging offers advantages in terms of data collection efficiency and coverage, the effectiveness of detection algorithms may vary based on factors such as image resolution, sensor specifications, and algorithm design (Ribeiro-Gomes et al., 2017).

To achieve this sub-objective, rigorous evaluations and comparative analyses will be conducted to benchmark the performance of existing detection methods. By assessing detection accuracy under various conditions and scenarios, this study aims to identify strengths and limitations of different algorithms. Furthermore, efforts will be made to validate the efficacy of proposed enhancements and improvements to existing detection techniques.

The assessment of detection accuracy is essential for ensuring the reliability and effectiveness of drone-based pothole detection systems in real-world applications. By addressing this sub-objective, the study seeks to provide insights that contribute to the advancement of pothole detection technology and pave the way for more efficient and accurate road maintenance practices.

Overall, the sub-objectives complement the main objective of integrating drones for pothole detection by focusing on key aspects that impact the performance and reliability of detection systems. Through a comprehensive approach encompassing both technical and environmental considerations, this study aims to develop innovative solutions that enhance the resilience and sustainability of road infrastructure management.

1.4 Scope and Limitations

1.4.1 Geographical Scope and Study Area Selection

Road infrastructure monitoring using drone technology offers immense potential for revolutionizing transportation infrastructure management. However, it is essential to define the scope of the study and acknowledge the inherent limitations. This section elaborates on the geographical scope, criteria for selecting study areas, and technological constraints, supported by relevant references to provide a comprehensive understanding.

The geographical scope of this study encompasses a diverse range of regions and road networks, selected to represent varying environmental conditions, traffic volumes, and pavement types. By examining pothole detection performance across different geographic contexts, this research aims to develop insights and methodologies that are applicable to a broad range of real-world scenarios. One key aspect of the geographical scope is the selection of study areas that exhibit distinct climatic conditions. Pothole formation and deterioration are influenced by factors such as temperature fluctuations, precipitation patterns, and freeze-thaw cycles (Baah et al., 2023). Therefore, it is essential to include study sites located in regions with different climatic profiles, ranging from temperate climates characterized by seasonal variations to tropical climates with high levels of rainfall and humidity (Roggero & Diara, 2024).

Furthermore, the study areas will be chosen to reflect a mix of urban, suburban, and rural environments, each presenting unique challenges and opportunities for pothole detection and maintenance. Urban areas typically experience higher traffic volumes and more intensive usage of road infrastructure, leading to accelerated wear and tear and increased frequency of pothole formation (Kong et al., 2017). In contrast, rural and remote regions may face challenges related to limited accessibility, sparse population density, and resource constraints, which can impact the efficiency and effectiveness of pothole detection and repair efforts (Rivas Casado et al., 2017).

The selection of study areas will also consider factors such as road network density, pavement type, and historical maintenance practices. High-density road networks with diverse pavement materials and traffic volumes offer opportunities to assess the performance of pothole detection algorithms under varying conditions (Suomalainen et al., 2018). Additionally, including roads with different surface materials, such as asphalt, concrete, and gravel, will allow for the evaluation of detection accuracy across different pavement types and compositions (Aleotti et al., 2017).

While the geographical scope of this study is extensive, it is essential to acknowledge certain limitations and constraints that may impact the generalizability of the findings. Variability in local regulations, funding availability, and institutional capacity may influence the implementation of pothole detection technologies and maintenance practices across different regions (Zhou et al., 2017). Additionally, logistical challenges such as access to study sites, data collection permissions, and weather conditions may pose constraints on the execution of field experiments and data collection activities (Torres-Rua, 2017).

Despite these limitations, the inclusion of diverse study areas and geographic contexts will enhance the robustness and applicability of the research findings, enabling transportation agencies and infrastructure managers to make informed decisions regarding pothole detection and maintenance strategies.

1.4.2 Technological Limitations and Constraints

The integration of drones for pothole detection is subject to various technological limitations and constraints that may impact the effectiveness and reliability of the detection process. These limitations encompass aspects related to UAV hardware and sensors, data processing and analysis algorithms, as well as operational considerations and regulatory requirements.

1. **UAV Hardware and Sensors:**

One of the primary technological limitations is the resolution and quality of aerial imagery captured by UAVs. While modern drones are equipped with high-resolution cameras capable of capturing detailed imagery of road surfaces, limitations in sensor capabilities, such as image distortion, noise, and limited dynamic range, may affect the clarity and accuracy of pothole detection (Ribeiro-Gomes et al., 2017). Furthermore, factors such as altitude, flight speed, and weather conditions can influence image quality and may require optimization of flight parameters to ensure adequate coverage and visibility (Kong et al., 2017).

Moreover, advancements in UAV sensor technology have addressed some of these limitations, with newer models featuring improved image stabilization, higher dynamic range, and enhanced low-light performance. For instance, the integration of global navigation satellite systems (GNSS) and inertial measurement units (IMUs) enables drones to maintain stable flight trajectories and capture high-quality imagery even in challenging environmental conditions. Additionally, the emergence of multispectral and hyperspectral sensors allows for the collection of spectral data beyond the visible spectrum, enabling more comprehensive analysis of road surface properties and conditions (Zhang et al., 2019).

2. **Data Processing and Analysis Algorithms:**

Another technological constraint is the computational complexity of data processing and analysis algorithms deployed for pothole detection. Image processing techniques such as feature extraction, segmentation, and pattern recognition are computationally intensive and may require specialized hardware or cloud computing resources to achieve real-time performance (Kikutis et al., 2017). Moreover, the accuracy and reliability of detection algorithms depend on the quality and diversity of training data, necessitating large annotated datasets for model training and validation (Aleotti et al., 2017).

Recent advancements in machine learning and artificial intelligence have significantly improved the efficiency and accuracy of pothole detection algorithms. Deep learning techniques, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), have demonstrated remarkable performance in image classification and object detection tasks. By leveraging large-scale datasets and parallel computing architectures, these algorithms can automatically learn and adapt to complex patterns in aerial imagery, enabling more robust and scalable pothole detection systems (Rivas Casado et al., 2017).

3. **Operational Considerations:**

Operational considerations such as flight planning, navigation, and safety protocols also pose challenges to the integration of drones for pothole detection. Ensuring safe and efficient operation of UAVs in urban environments requires compliance with regulatory requirements, airspace restrictions, and privacy concerns (Baah et al., 2023). Additionally, factors such as battery life, flight endurance, and environmental conditions may limit the duration and scope of drone missions, requiring careful optimization of operational parameters and logistics (Sandino et al., 2017).

Furthermore, the integration of drones into existing road maintenance workflows and institutional practices may face resistance or barriers due to factors such as organizational culture, stakeholder perceptions, and resource constraints (Ridolfi et al., 2017). Transportation agencies and infrastructure managers must navigate these socio-technical challenges to successfully implement drone-based pothole detection solutions and realize the potential benefits of this technology.

In summary, while drone-based pothole detection offers significant promise for enhancing the efficiency and effectiveness of road maintenance operations, it is essential to recognize and address the technological limitations and operational constraints that may impact its implementation and scalability. By understanding these challenges and developing strategies to overcome them, this study aims to advance the state-of-the-art in UAV-based infrastructure monitoring and contribute to the development of more resilient and sustainable transportation systems.

1.5 Organization of the Thesis

1.5.1 Overview of Chapter Structure and Contents

The thesis is meticulously structured to provide a thorough exploration of the integration of drones for pothole detection in road infrastructure monitoring. Each chapter is dedicated to examining distinct aspects of the research objectives, offering a comprehensive analysis supported by relevant references and empirical evidence. The following overview provides more detailed descriptions of each chapter's contents:

Chapter 1: Introduction

Chapter 1 provides an introduction to the research and the reasons why it was pursued. To this end, the research gaps are described along with the objectives that were designed to overcome the gaps and take advantage of the research opportunities.

Chapter 2: Literature Review

Chapter 2 serves as the cornerstone of the thesis, offering an extensive review of existing literature on road infrastructure monitoring, pothole detection techniques, and the utilization of drones in transportation infrastructure management. It provides a comprehensive overview of the historical development of road monitoring practices, the evolution of pothole detection methods, and the emergence of drone technology in infrastructure management. The chapter synthesizes key findings from peer-reviewed studies, industry reports, and governmental publications to identify gaps in knowledge and areas for further research. Moreover, it highlights the theoretical frameworks and conceptual models that underpin the integration of drones for pothole detection, laying the groundwork for the subsequent chapters.

Chapter 3: Research Methodology

Chapter 3 meticulously elucidates the research methodology employed in the study, outlining the data collection procedures, experimental design, and analytical techniques utilized throughout the research process. It provides detailed descriptions of the methods used to integrate drones into the pothole detection process, including the selection criteria for study areas, the deployment of UAVs, and the collection of aerial imagery. Additionally, the chapter discusses the development of algorithms for pothole detection and the validation methods employed to assess detection accuracy. By transparently documenting the research methodology, Chapter 3 ensures the reproducibility and rigor of the study's findings.

Chapter 4: Case Studies

Building upon the methodological framework outlined in Chapter 3, Chapter 4 delves into the geographical scope of the study and provides a rationale for the selection of study areas. It conducts a detailed analysis of chosen regions, considering factors such as climatic conditions, pavement types, and traffic volumes to ensure the representativeness and diversity of environmental contexts. The chapter also discusses the logistical considerations involved in accessing study sites, obtaining necessary permissions, and mitigating operational challenges. By thoroughly examining the geographical scope and study area selection process, Chapter 4 establishes the foundation for the empirical investigations conducted in subsequent chapters.

Chapter 5: Result and Discussions

Chapter 5 critically explores the technological challenges and constraints associated with drone-based pothole detection. It examines issues related to UAV hardware, sensor capabilities, data processing algorithms, and operational considerations that may impact the effectiveness and reliability of detection systems. The chapter discusses strategies for overcoming technological limitations, such as optimizing flight parameters, enhancing sensor performance, and refining detection algorithms. Moreover, it addresses operational constraints, including regulatory requirements, airspace restrictions, and safety protocols, that must be navigated to successfully implement drone-based monitoring solutions. Through a comprehensive analysis of technological challenges, Chapter 5 provides insights into the complexities of integrating drones into road infrastructure monitoring practices.

Chapter 6: Conclusion and Future Research:

The final chapter, Chapter 6, offers a conclusive summary of the key findings presented in the thesis. It reaffirms the main contributions to the field and outlines avenues for future research and innovation. Additionally, the chapter emphasizes the importance of continued collaboration and interdisciplinary engagement in addressing critical challenges and fostering the development of more resilient and sustainable transportation systems. By providing a roadmap for future research directions, Chapter 6 ensures that the insights gained from the study contribute to ongoing advancements in infrastructure monitoring and pothole detection technologies.

Chapter 2

2. Literature Review

This section provides an introductory overview of the importance of road infrastructure monitoring and the critical role that drones play in weather-aware pothole detection. It emphasizes the significance of this research in improving road safety, reducing maintenance costs, and enhancing transportation efficiency.

Literature Search Strategies

1. **Selection of Databases:** To ensure an exhaustive review of the literature, multiple academic databases were meticulously chosen. These databases include IEEE Xplore, ScienceDirect, PubMed, Web of Science, Scopus, and Google Scholar. By leveraging these platforms, a diverse range of scholarly publications relevant to road infrastructure monitoring and drone technology was accessed.
2. **Keywords and Search Terms:** A comprehensive list of keywords and search terms was curated to capture the breadth of research on integrating drones for weather-aware pothole detection. These keywords included variations such as "drones," "pothole detection," "weather-aware," "road infrastructure," "monitoring," "machine learning," and "artificial intelligence." The iterative refinement of these terms ensured the inclusivity of relevant studies.
3. **Inclusion and Exclusion Criteria:** To maintain the quality and relevance of the literature review, specific inclusion and exclusion criteria were established. Inclusion criteria encompassed peer-reviewed papers published in reputable journals or conference proceedings, focusing on weather-aware pothole detection using drones. Exclusion criteria involved filtering out duplicate publications, conference abstracts lacking full papers, and articles not directly related to the research topic.
4. **Data Collection and Screening Process:** The data collection process commenced with a systematic search using the identified keywords across the selected databases. Search results were imported into reference management software to facilitate data organization and removal of duplicates. Subsequently, titles and abstracts of the remaining articles were meticulously screened to assess their relevance based on the established inclusion and exclusion criteria.

5. **Full-Text Review and Selection:** Selected papers underwent a comprehensive full-text review to determine their suitability for inclusion in the literature review. Each paper was scrutinized to ensure alignment with the research objectives and relevance to the research questions. Only papers meeting the established criteria were included in the final review.
6. **Cross-Referencing and Citation Tracking:** To augment the comprehensiveness of the literature review, a cross-referencing and citation tracking approach was adopted. This involved examining the reference lists of selected papers to identify additional relevant studies that might have been overlooked during the initial database search.

By meticulously implementing these literature search strategies, the literature review aims to provide a comprehensive analysis of existing research on integrating drones for weather-aware pothole detection in road infrastructure monitoring. This approach ensures the inclusion of high-quality and pertinent studies, thereby enhancing the credibility and reliability of the research findings.

2.1 Traditional Methods of Road Infrastructure Monitoring

In this section, we explore traditional methods of road infrastructure monitoring, particularly focusing on visual inspection techniques. These methods involve manual surveys conducted by trained personnel to identify potholes and other pavement defects along roadways. Visual inspections typically entail visually scanning the road surface for signs of distress, such as cracks, potholes, and surface irregularities. The five primary approaches used in pothole detection research are vision-based, 3D reconstruction-based, vibration-based, LiDAR-based, and machine learning-based.(Joshi 2020).

2.1.1 Visual Inspection Techniques

Maintaining top-notch road infrastructure is essential for traffic safety and supporting economic activity. However, the usual methods of checking roads are manual, slow, and subjective. Visual checks done by people can vary due to factors like tiredness or different lighting conditions. This can lead to delays in finding and fixing road issues like potholes and speed bumps. These delays not only increase safety risks but also cause more damage to vehicles. Therefore, there's a need for better and quicker inspection methods. (Anuja Garande, 2024)

Road damages have a direct impact on transit users and contribute to increased risks of road accidents. Thus, acquiring data regarding the physical conditions of road surfaces and damages is imperative for various applications including planning, maintenance, and budget allocation (Chaithavee, S 2023).

Transportation agencies allocate a considerable portion of their budget to monitor and maintain road pavements. Pavement distress can be identified through manual surveys, which involve visual inspections of pavement images captured by inspection vehicles (Ce Zhang et al,.2023).

The conventional approach often relies on image edge detection techniques for crack detection. A Sobel edge detector is commonly implemented following image smoothing and noise removal filters to identify cracks (Ce Zhang et al,.2023). However, there are limitations to this method. To address these limitations, the CrackTree algorithm was proposed. Initially, an algorithm was developed to eliminate pavement shadows. Then, a crack probability map was constructed using tensor voting, which effectively mitigated noise and fragmentation issues. Subsequently, a graph model was constructed by sampling crack seeds from the probability map. A Minimum Spanning Tree (MST) of the graph was generated, followed by recursive edge pruning within the MST to identify the final crack curves. The results demonstrated that CrackTree achieved a precision of 0.79 on a dataset consisting of 206 images. Although this performance surpassed that of CrackIT, it was deemed insufficient for practical application (Ce Zhang et al,.2023).

Potholes demand urgent attention to reduce their role in potential accidents. According to the World Health Organization (WHO), road accidents are projected to become the 5th leading cause of death by 2030. This alarming prediction has sparked considerable interest among civil researchers regarding the significance of potholes. In many developing nations, manual inspection methods are employed to identify potholes, leading to inaccuracies due to their reliance on individual experience. These manual techniques involve time-consuming and costly human interventions (Asad et al., 2022).

2.1.2 Ground-based Sensors and Surveys

With the rapid advancements in sensing technologies, a wealth of geospatial data can now be gathered from various sensors including cameras, multi- and hyper-spectral scanners, synthetic aperture radar (SAR), and laser scanners. These sensors are deployed across a range of platforms such as satellites, aircraft, unmanned aerial/ground vehicles, boats, trains, cars, and even handheld devices carried by humans. The geometric and semantic information extracted from these datasets is crucial for making informed decisions and addressing real-world challenges. However, accurately and reliably extracting information from such diverse datasets remains a significant challenge within cartography and other geoinformation communities (Jonathan Li, 2021).

An innovative sensor-based network called "BusNet" has been proposed for monitoring road conditions, with cameras mounted on public transport buses. This system utilizes multiple sensors and GPS for fast, sensitive, and cost-efficient monitoring. However, it is noted that this system may not be suitable for all scenarios, as adverse weather conditions could potentially damage the sensors, leading to performance degradation of the BusNet (Asad et al., 2022).

To enhance financial savings, ensure public safety, and establish durable road infrastructure, the implementation of Structural Health Monitoring (SHM) applications for roads is imperative. This project will utilize a terrestrial laser scanner (TLS) for data collection, primarily for monitoring purposes (Arpit Bhatt et al., 2022).

An accelerometer, an electromechanical device capable of measuring velocity changes or ranges in single or multiple directions, serves a pivotal role in this endeavor. Functionally, it measures the physical acceleration experienced by a mass due to gravitational force, converting it into an electrical signal. In practical terms, accelerometers gauge the acceleration of a mass connected to a spring. As the mass accelerates, it exerts force on the spring, causing either extension or compression depending on the acceleration's direction. The displacement of the mass is then proportional to the acceleration.Various types of accelerometer sensors exist, categorized based on their output technology. These include piezoelectric accelerometers, piezoresistive accelerometers, capacitive accelerometers, and magneto resistive accelerometers. Each type operates differently, utilizing alterations in voltage, resistance, capacitance, or magnetic domains to measure acceleration.In road monitoring applications, the accelerometer's three axes serve specific functions: the X-axis monitors vehicle turns, the Y-axis detects road slope, and the Z-axis tracks upward and downward vehicle movements, primarily for detecting road defects. Accelerometer sensors have been traditionally employed in engineering fields such as vehicle airbag deployment and crash detection. However, their recent use in road defect detection has gained traction, utilizing accelerometer data for road surface condition monitoring and anomaly detection.One significant advantage of accelerometer sensors is their ability to function in a constant and stable position, minimizing noise signals. Nonetheless, a drawback of some accelerometer sensors lies in their fixed time and internal constant domain, limiting their applicability in certain scenarios (Alrajhi et al., 2023).

This study highlights the effectiveness of utilizing accelerometers for detecting pothole defects, particularly in the context of road maintenance within the RGIPT campus area. A systematic survey of road patches and potholes spanning a 2 km stretch is being conducted using accelerometers.In this innovative approach, smartphones equipped with accelerometers are employed to upload positional data and identify any uneven road surfaces to the cloud as vehicles traverse over them. By leveraging accelerometers, potential internal damages to pavements can be detected even before they manifest on the road's surface.The cloud-based system issues alerts about uneven road surfaces to ensure safe and smooth driving for other vehicles approaching the area. Operating on a simple smartphone setting, the system utilizes raw accelerometer measurements, capable of capturing irregular driving patterns or sudden brakes.Data collected from mobile phones and sensors are utilized for ongoing monitoring and prediction of road surface conditions. The classification and treatment of pavement defects are tailored based on their specific characteristics and severity levels (Arpit Bhatt et al., 2022).

2.1.3 Remote Sensing Technologies

The section on Remote Sensing Technologies delves into the application of tools like satellite imagery and LiDAR (Light Detection and Ranging) for monitoring road infrastructure from aerial and space-based platforms.

Sensors play a pivotal role in identifying road defects, serving as the cornerstone for initiating necessary treatments. There exists a diverse array of sensors tailored to detecting road defects, each suited to specific scenarios. Additionally, integrated sensor systems offer advanced capabilities for both manual and automated data collection. These sensors gauge vehicle responses to defects such as potholes, bumps, and cracks.The discussion proceeds by elaborating on common single sensors, detailing their functionalities and applications. Subsequently, the focus shifts to integrated sensor platforms, wherein single sensors evolve and merge into a unified device. This integrated sensor platform streamlines defect detection through automation, thereby addressing road condition issues more efficiently (Alrajhi et al., 2023).

In recent years, especially with the rapid urbanization, the detection and segmentation of buildings from aerial images have emerged as significant and challenging research areas in both remote sensing and computer vision fields. Distinguishing each pixel as belonging to either a building or a non-building class presents challenges due to variations in building sizes and shapes, as well as the striking similarities between buildings and non-buildings. Additionally, the pixel values within aerial images exhibit substantial variance within the same class and comparatively small differences between classes. These complexities underscore the difficulty of accurately and effectively identifying buildings in aerial imagery (Batuhan Sariturk et al., 2023).Researchers have explored using additional sensors like laser scanners or LiDARs to provide depth information for defect detection. This survey paper reviews road surface defect detection studies, categorizing them based on input data types and methodologies, and discusses challenges and open problems associated with these techniques (Jongmin Yu 2023).

Light Detection and Ranging (LiDAR) is a remote sensing technology that utilizes light radiation to gather information about subjects without physical contact. In the domain of road defect detection, LiDAR plays a crucial role as a sensor. The process involves emitting a light pulse from the sensor, which subsequently bounces off the target subject and returns to the sensor. By calculating the time taken for this reflection to occur, the distance between the scanner and the scanned subject can be determined.There are two primary types of LiDAR systems: scanning LiDAR and non-scanning LiDAR. Scanning LiDAR includes single-line and multi-line variants, where laser beams are utilized to generate contour maps. Non-scanning LiDAR, such as 3D-flash LiDAR, offers data over a given region rather than a singular point. These systems differ in components, system structure, working principle, global improvements, and associated challenges.LiDAR boasts high-resolution, long-range 3D data collection capabilities, even in low-light or adverse weather conditions. Integrating LiDAR data with camera and millimeter-wave data enhances coverage across diverse driving conditions comprehensively. Furthermore, LiDAR accuracy enables the identification of human statuses, such as riding, walking, and movement speed or direction. Consequently, it stands as a critical sensor for Level 3 or higher-level autonomous vehicles.Data collection for LiDAR can be conducted via airborne, spaceborne, or terrestrial means. Mobile Laser Scanning (MLS) represents a prevalent method for transportation applications, as it enables detailed data capture of road features. In MLS, systems mounted on vehicles traverse the desired highway, capturing 360-degree images of the roadway. Unlike accelerometer sensors, LiDAR does not require proximity to the measured object for data collection, as vehicles are equipped with Global Navigation Satellite System (GNSS) receivers and inertial measurement units (IMUs) to provide precise sensor status information.Despite its advantages, LiDAR systems can be costly, and their effectiveness is limited in heavy rain, snow, or foggy conditions due to interference with the light beam path (Alrajhi et al., 2023).

A LiDAR camera mounted on a moving vehicle generates a 3D point cloud, serving as a valuable tool for monitoring road conditions. Poorly maintained roads can have detrimental effects, including reduced productivity, increased fuel consumption, heightened mechanical wear, hazardous operating conditions, driver discomfort, and elevated rolling resistances. Additionally, road management agencies face challenges with pavement repair methods and struggle with the financial resources required to maintain existing road networks in optimal condition (Arpit Bhatt et al., 2022).

Recent advancements in technology, including unmanned aerial vehicles (UAVs), sensors, and satellites, have led to increased accessibility to high-resolution aerial images. These images have become the preferred data source for building segmentation applications, marking a new era for the community. The availability of high-resolution aerial images has refined the texture, structure, and spectral information of buildings, opening new avenues for research and application in this field (Batuhan Sariturk et al., 2023)

2.2 Advancements in UAV-Based Monitoring Techniques

Advancements in UAV-based monitoring techniques are reshaping infrastructure monitoring practices, with drones assuming a pivotal role. Equipped with advanced cameras and sensors, these unmanned aerial vehicles (UAVs) can capture high-resolution imagery of various infrastructural elements, including roads, bridges, and buildings.

UAVs, commonly known as drones, have garnered widespread usage and attention over the past decade. The majority of studies highlight the prevalence of multirotor UAVs due to their simplicity in control mechanisms and high precision in positioning. While other types of UAVs are also utilized, their numbers are comparatively lower. Despite their utility, practical implementation of UAVs in various application scenarios faces several limitations. Among these, flight endurance emerges as a critical constraint, primarily due to the limited power supply provided by batteries. Addressing this challenge necessitates innovative solutions such as the development of different battery types employing hybrid systems or internal combustion engines. Another promising approach involves the utilization of docking stations, which can recharge or swap batteries, store UAVs, and even facilitate communication tasks. By mitigating the battery endurance issue, docking stations propel UAVs towards greater autonomy and efficacy within monitoring systems (Syed et al., 2023).

2.2.1 Role of Drones in Infrastructure Monitoring

In recent years, the construction industry has undergone a significant transformation, propelled by technological advancements. Drones have emerged as pivotal tools in this evolution, revolutionizing the planning, execution, and maintenance of construction projects. With sophisticated sensors, cameras, and GPS technology, drones offer unparalleled capabilities to capture real-time data, generate precise 3D models, and conduct remote inspections. This review paper aims to provide a comprehensive overview of drones' applications in construction, elucidating their impact across various project phases and highlighting the potential benefits they offer (Hee-wook et al., 2023).

Infrastructure projects pose unique challenges, requiring meticulous control over daily activities, costs, and resources to adhere to project timelines and meet deadlines. Drones can significantly contribute to the success of these projects by providing real-time monitoring and data collection capabilities, facilitating efficient management of resources and ensuring adherence to project schedules (Vikas et al., 2019).

The utilization of drones in site surveys has significantly transformed the landscape of infrastructure projects. Traditionally, conducting site surveys required heavy machinery, expensive tools, and ample resources, rendering it a costly endeavour. Aerial photography, typically conducted via helicopters, further escalated expenses. However, drones offer a cost-effective alternative, providing live images of the site without the need for extensive resources or expensive equipment. This not only saves costs but also enhances efficiency by offering real-time insights into the current state of the site, thereby streamlining the survey process (Vikas et al., 2019).

Moreover, accurate estimation of road infrastructure heavily relies on identifying key features such as potholes. The effectiveness of this estimation hinges upon the type and quantity of road features considered and the efficacy of the analysis algorithms. Too many disparate features or closely resembling ones can pose challenges in accurately assigning events to their respective features. Conversely, a sparse definition of features may only yield a rough estimation of road infrastructure conditions, limiting the precision of analysis. Striking the right balance in feature selection is essential for achieving accurate and comprehensive assessments of road infrastructure (Johannes et al., 2017).

2.2.2 Applications of UAVs in Pothole Detection

Drones offer effective diagnostics, detection, and supervision capabilities for aerial tasks, thanks to their advanced built-in computers, thermal scanners, high-resolution cameras, and other tools. In the healthcare sector, the use of drones has become increasingly vital. They facilitate the quick and efficient delivery of samples, lab reports, and other health-related essentials for health professionals. Drones have also played a crucial role in enforcing public health rules during the COVID-19 pandemic, using audio and visual alerts to ensure compliance. Their capabilities for patrolling and monitoring in various developed countries have been remarkable, with drones assisting in reporting rules violations, diagnosing cases, and even disinfecting public areas. (Yue Wang et al., 2022)

Mapping with drones involves creating precise maps and models of construction sites by utilizing aerial imagery and photogrammetry techniques. Drones capture detailed aerial images efficiently, covering expansive areas and offering a clear visual depiction of the site's characteristics. By analyzing these images, photogrammetry techniques produce both 2D and 3D maps, including topographic maps that showcase elevations, contours, slopes, and other geographical attributes. This method aids in accurately understanding the terrain and features of the construction site, facilitating informed decision-making and effective planning for construction projects. (Hee-wook et al., 2023)

The timely and effective rehabilitation of damaged roads is crucial for road maintenance, necessitating a method to detect road surface distress efficiently and cost-effectively. Unmanned aerial vehicles (UAVs) present a compelling option for road condition monitoring, offering advantages such as high flexibility, low cost, and easy maneuverability. UAV photogrammetry has found applications across various fields due to advancements in both hardware and software. Serving as a cost-effective alternative to manned aerial photogrammetry, UAV photogrammetry holds significant potential in geomatics applications, including agriculture, forestry, archaeology, architecture, environmental monitoring, emergency management, and traffic surveillance (Yumin Tan et al., 2019).

In today's era, Unmanned Aerial Vehicles (UAVs), commonly known as drones, have diverse applications across various industries. They are utilized for military purposes, agricultural crop quality prediction, landscape photography, and even goods delivery by large organizations. The versatility of drones extends across every industry and vertical, showcasing their boundless utility and potential impact (Hema Malini et al., 2021).

2.2.3 Case Studies of UAV-Based Monitoring

Presents real-world case studies and projects where UAVs have been deployed for monitoring road infrastructure, illustrating their effectiveness in identifying and quantifying pavement distresses.

In Hema Malini's (2021) paper, a method is introduced to streamline the process of pothole detection utilizing camera-equipped Unmanned Aerial Vehicles (UAVs), commonly referred to as drones. This system is augmented with geotagging capabilities, allowing it to promptly report the presence of potholes to a central database accessible by relevant authorities and the general public. The identified potholes are then pinpointed on an open-source map, providing road users with crucial information to exercise caution. This not only enhances public safety but also expedites response times for concerned authorities. To enable efficient detection, the model is trained utilizing the YOLOv3 algorithm, which ensures accurate detection of potholes, including those obscured by water, while distinguishing them from dark road patches. The findings of the study demonstrate a commendable accuracy rate of 85%, coupled with minimal occurrences of false negatives and false positives.

In their study, Kim et al. (2022) delve into the significance of potholes as road defects that not only damage vehicles but also pose risks to driver safety and contribute to traffic accidents. Efficient management of potholes is crucial for ensuring driver safety and the smooth flow of traffic in complex road environments. Traditionally, pothole detection relied on visual inspection by human experts. However, recent advancements have led to the development of automated pothole-detection methods that leverage various technologies, including sensors and signal processing.The automated pothole-detection methods discussed in the paper are categorized into three types based on the technology used in the pothole-recognition process: vision-based, vibration-based, and 3D reconstruction-based methods. The study compares these methods and provides a comprehensive analysis of their strengths and weaknesses. Furthermore, it elaborates on the detection process and technology proposed in the latest research related to automated pothole detection for each method(Toral et al 2023). Additionally, the paper outlines future development plans for technology that builds upon the findings of these studies, offering insights into the direction of advancements in automated pothole detection. By summarizing the current state of automated pothole-detection methods and outlining future research directions, the study contributes to the ongoing efforts to enhance road safety and transportation infrastructure management.

In a study by Ji-Won Baek (2020), the challenge of detecting specific objects such as potholes, cracks, shadows, and lanes in road damage images was addressed. The proposed method introduced a pothole classification model utilizing edge detection in road images. Initially, RGB image data containing various objects, including potholes, was converted to grayscale to reduce computational complexity. An object detection algorithm was then employed to identify and remove all objects except for potholes, assigning a pixel value of 255 to process them as background. Subsequently, the contour of the pothole was extracted through edge detection to capture its characteristics. Finally, potholes were detected and classified using the You Only Look Once (YOLO) algorithm. The performance evaluation of the model included assessing the distortion rate and restoration rate of the image, along with the validity and accuracy of the classification. The evaluation results indicated the mean square error (MSE) of the distortion rate and restoration rate of the proposed method, demonstrating its effectiveness in pothole detection and classification.

In their paper, Monte et al. (2020) addresses the challenges posed by the exponential growth of the vehicle fleet worldwide, particularly in Brazil, where there has been a staggering 80% increase in vehicle numbers between 2009 and 2019. This surge has led to a significant strain on the country's road infrastructure, which currently only covers approximately 12% of its total network with paved roads. As a result, the increased vehicular traffic has accelerated pavement deterioration, especially under the weight of heavy vehicles. The study aims to introduce an innovative methodology for inspecting road networks in Brazil to identify visible pathologies using Unmanned Aerial Vehicles (UAVs). The utilization of UAVs offers a promising solution to efficiently survey vast stretches of highways, allowing for the identification of pavement issues in a timely manner. To validate their approach, inspections were conducted on two important highways in the state of Paraiba. The results of these inspections revealed various pathologies, including interconnected cracks, alligator cracking, landslides, longitudinal and transversal cracks, potholes, and patches. These findings underscore the efficacy of the proposed UAV-based methodology for highway inspections, demonstrating its ease of application and objectivity in identifying pavement distress.

In their study, Pan et al. (2018) highlights the significance of asphalt roads in land transportation systems and the inevitable deterioration they undergo over time, leading to various pavement distresses such as potholes and cracks. To enhance the efficiency of pavement inspection, the study explores the use of non-destructive remote sensing techniques, including digital images, Light Detection and Ranging (LiDAR), and radar. Multispectral imagery, capable of capturing both spatial and spectral features of objects, has emerged as a valuable tool in remote sensing applications. In their research, the authors leverage multispectral pavement images acquired by Unmanned Aerial Vehicles (UAVs) to differentiate between normal pavement and pavement damages like cracks and potholes. They employ machine learning algorithms such as support vector machines, artificial neural network, and random forest to analyze the acquired imagery. The study conducts a comparative analysis of different data types and models to evaluate their performance in pavement damage detection. The findings suggest that a UAV remote sensing system offers a promising approach for monitoring asphalt road pavement condition. The insights gleaned from this research can serve as decision support for road maintenance practices, aiding in the timely identification and remediation of pavement distresses.

In a study conducted by Madokoro et al. (2021), drones were employed for in situ measurements, demonstrating their versatility and accessibility in monitoring challenging terrains and remote areas. The use of a lightweight, cost-effective multi-sensor system enabled the capture of various atmospheric phenomena such as PM, temperature, and humidity, thus generating comprehensive datasets for environmental monitoring. Real-time data transmission via long-range wireless communication facilitated seamless connectivity between drones and ground stations. Furthermore, the development of four prototype brackets optimized space and weight distribution for efficient sensor mounting. Validation experiments were conducted to ensure sensor accuracy, with flight measurements carried out across diverse environments to generate original datasets for analysis. Leveraging LSTM networks, predictions of regional PM2.5 trends were made, thereby enhancing understanding of air quality dynamics and supporting global efforts against air pollution.

In their investigation, Baah (2023) delved into the pollution levels near roadways utilizing data obtained from Unmanned Aerial Vehicles (UAVs). Throughout the winter season, they collected 18 snow samples from both sides of the Caspian Highway in Moscow. Through the analysis of the chemical composition of these samples, the study identified a total of 35 chemical elements, predominantly metals. Of particular interest was the examination of the feasibility of utilizing remote sensing data acquired from UAVs to detect specific metals, including Aluminium, Barium, Iron, Potassium, and Sodium, present in snow cover due to dust dispersal from roadways. The findings of the study lend support to the notion that UAV sensing data can indeed serve as an effective tool for monitoring air pollution originating from roadways.

In their review, Loots et al. (2022) shed light on the increasing adoption of unmanned aerial vehicles (UAVs) within the mining sector, highlighting their potential to enhance the efficiency and cost-effectiveness of remote sensing practices. The review aims to provide stakeholders with valuable insights to identify opportunities for the adoption, refinement, and innovation of UAV applications in mining. Employing a strategic approach and practical screening criteria, the review meticulously identifies potential research avenues to address key inquiries within the mining sector. After a thorough screening process, 72 documents were analysed and categorized into different phases of mining activities, including exploration, development, exploitation, and reclamation. Among the fifteen identified applications, the majority were focused on the exploration phase, with topographic surveys, reclamation monitoring, and slope management emerging as notable research areas. Multi-rotor vehicles were predominantly favoured for various applications, while photogrammetry emerged as the most frequently utilized remote sensing technique. However, the review also highlights several challenges hindering the broader utilization of UAV technologies in mining, such as complexity, cost, and compatibility issues between sensors and UAV platforms. Additionally, the review primarily examined published papers in academic journals, suggesting a need for future studies to incorporate empirical data on the latest UAV applications in mining to further enrich the understanding of their potential benefits and limitations in this industry.

In Micko et al.'s (2023) study, the focus is on advancing the smart city concept through the implementation of intelligent transportation systems, facilitated by the Internet of Things (IoT) technology. IoT serves as a fundamental tool for digitalization and automation in this context, enabling automatic data collection in transportation management. This is achieved through a network of sensors, actuators, and control units deployed across edge, fog, and cloud layers.

The study introduces a taxonomy of sensors specifically tailored for monitoring tasks related to motion detection and object tracking within intelligent transportation systems. By categorizing sensors based on various criteria such as working principles and installation methods, the study enables effective comparison of sensor systems. To further explore the effectiveness of sensor systems in motion detection and object tracking tasks, the study conducts a comprehensive literature review. The survey of sensor systems used in these tasks provides insights into their performance in event measurement, sensing, or classification. Drawing conclusions from this review, the study proposes a universal sensor system architecture designed for common monitoring tasks in intelligent transportation, particularly those involving motion detection and object tracking.

According to Krisztina Pintér's article (2022), the creation of high spatial resolution and geolocation accuracy canopy Evapotranspiration (ET) maps is crucial for evaluating small plot field trials. However, obtaining imagery of sufficient quality remains a challenge. The paper proposes a solution utilizing a UAV-based thermal/RGB integrated imaging system constructed around the RaspberryPi (RPi) microcomputer. The imagery captured serves as input for the two-source energy balance model pyTSEB to derive the ET map. The system's flexibility and modularity rely on the RPi's multiple interfaces and the software development kit (SDK) for the thermal camera. Installed on the RPi, the SDK triggers cameras, retrieves and stores images, and gathers geolocation information from an onboard GNSS rover for PPK processing. This setup enables the acquisition of 8 cm spatial resolution thermal imagery from a 60 m flight height and less than 7 cm geolocation accuracy of the mosaicked RGB imagery. Validation against measured latent heat fluxes from eddy covariance stations at two locations shows a Root Mean Square Error (RMSE) of 75 W/m2 over a two-year study period.

According to Zhou's study (2022), detecting road defects is crucial for ensuring traffic safety and efficient maintenance. Intelligent detection technologies have been developed to enhance the efficiency of identifying road defects, leading to more targeted maintenance and management efforts. These technologies effectively address challenges such as high costs and low efficiency associated with manual inspection, thereby improving the quality of road construction and safeguarding lives and safety.The study focuses on intelligent road defect detection and reviews commonly used detection equipment, including cameras, Ground Penetrating Radar (GPR), Light Detection and Ranging (LiDAR), and Inertial Measurement Units (IMU). It systematically traces the evolution and development of road defect detection technology, highlighting common challenges and proposing corresponding improvement suggestions. Finally, the study discusses future development trends in road detection technology, providing practical insights for its continued advancement.

In their paper, Elena Ridolfi (2017) investigates the accuracy of models derived from drone surveys, with a specific focus on the placement of ground control points (GCPs) used for georeferencing. The study concentrates on assessing how different configurations of GCPs influence the accuracy of resulting three-dimensional (3D) models, particularly in the context of analysing the upstream face of a double arch masonry dam. Drone-acquired images are utilized to construct the 3D model required for vulnerability analysis. The study explores various configurations of GCPs to evaluate their impact on model accuracy. For each configuration, dense point clouds are generated, facilitating thorough analysis. To assess accuracy, the coordinates of check points extracted from the model are compared with true coordinates obtained through traditional topography methods. The ultimate goal of the research is to provide guidance on the optimal placement of GCPs, not only for dam surveys but also for surveys involving tall structures. By enhancing survey reliability, accuracy, and efficiency, the findings of this study aim to contribute to the improvement of georeferencing practices in drone-based surveys.

In a study conducted by Syed et al. (2022), the versatile applications of drones, also known as unmanned aerial vehicles (UAVs), are explored across diverse sectors, ranging from military operations to construction, mapping, and medical services. These UAVs offer unique advantages such as extended flight time, manoeuvrability, and access to remote areas, making them increasingly valuable in various industries. Despite their versatility, drones face challenges such as limited battery life and flight autonomy. The review conducted by Syed et al. delves into the significance of drones, highlighting their capabilities and the obstacles they encounter. It discusses different aspects including the types of drones available, their wide-ranging applications, and ongoing efforts towards standardization and security measures. Furthermore, the review identifies areas for further research and development aimed at addressing the existing limitations and enhancing the effectiveness of UAVs across different domains. By exploring these aspects comprehensively, the study provides valuable insights into the current landscape of drone technology and its potential for future advancements.

In Silva's (2018) paper, the focus lies on the impact of road pavement anomalies on drivers, passengers, and road infrastructure, emphasizing the associated risks of mechanical failure and accidents. The author highlights the substantial annual investments made by governments in road maintenance, often resulting in traffic congestion, particularly in urban areas. The paper delves into the performance discrepancy observed when deploying a road anomaly detection and identification system in controlled environments versus real-world scenarios, where the system exhibited subpar performance. To comprehensively analyze system performance, the study scrutinizes training datasets, assesses attribute complexity using Principal Component Analysis (PCA) techniques, and examines attributes associated with each anomaly type. A notable aspect of the analysis involves the use of acceleration standard deviation attributes to visually represent the distribution of different anomaly classes in the Cartesian coordinate system. Through this approach, the paper aims to shed light on the challenges encountered in road anomaly detection, with the overarching goal of informing the design and implementation of an enhanced version of the system. Ultimately, the objective is to develop and deploy a road anomaly detection service capable of providing vital information about road conditions to both drivers and government entities, thereby contributing to improved road safety and infrastructure maintenance practices.

According to Jakubec et al. (2023) and (Khaple et al2023), potholes represent a significant problem for road safety and infrastructure, posing risks to both vehicles and pedestrians. Detecting potholes in real-time and with high accuracy, particularly under various lighting conditions, is crucial for the safety of road users and the timely repair of these hazards. With the increasing availability of cameras on vehicles and smartphones, there is growing interest in using computer vision techniques for pothole detection. Convolutional neural networks (CNNs) have shown promising results for object detection tasks, including pothole detection. This study provides an overview of computer vision algorithms used for pothole detection. Experimental results evaluate the performance of the latest CNN-based models under different real-world road conditions, such as rain, sunset, evening, night, and clean conditions. The study compares both conventional and the newest architectures from the region-based CNN (R-CNN) and You Only Look Once (YOLO) families(Ahmed 2021). YOLO models exhibit faster detection response and higher accuracy in detecting potholes under clear, rain, sunset, and evening conditions. Conversely, R-CNN models perform better in low-visibility conditions at night. These findings offer valuable insights into the performance of different CNN models for pothole detection in real road conditions, aiding in the selection of the most suitable model for specific applications. Recent studies have explored the integration of photogrammetry and convolutional neural networks (CNNs) for automated pothole detection and classification, achieving high accuracy and efficiency in pavement condition assessment (Ranyal, E., Sadhu, A., & Jain, K. (2023).

In a study conducted by Thom et al. (2023), the serious threat posed by potholes on roads, attributed to factors such as water damage, freeze-thaw cycles, and pavement deterioration, was emphasized. The repair of 1.7 million potholes in the UK in 2021 underscored the significant economic, social, and environmental impacts associated with them. Despite their prevalence, there is currently no tool available to forecast pothole occurrences across road networks. The study aimed to investigate pothole formation, its correlation with other road distress types, and severity levels, while also developing a straightforward predictive tool for estimating pothole numbers in a road network based on its condition. By utilizing extensive pothole and surface distress data from Greater London's road network spanning 2017 to 2020, the study employed ArcGIS's 'Spatial density' and 'join' tools to analyze the spatial density of potholes (PSD) in relation to surrounding road conditions. Through correlating PSD with indicators such as road condition index and crack intensity, the study established a predictive model for pothole occurrences based on the length and condition of road sections under scrutiny. The findings of the study revealed a notable concentration of potholes in sections with deteriorated conditions, highlighting the feasibility of predicting pothole occurrences using PSD with reasonable accuracy. Furthermore, the study emphasized the heightened susceptibility of sections with low crossfall to pothole formation, likely due to water accumulation and ensuing damage.

In a study conducted by Talha et al. (2024), the significant impact of potholes on driving safety and quality was highlighted, emphasizing the importance of timely mitigation for the well-being of road users. However, efficient maintenance relies on effective pothole detection methods. Current approaches, which rely on manual inspection and user reports, are subjective, prone to inaccuracies, and laborious. An ideal solution would be accurate, automated, and cost-effective, covering detection, localization, and size estimation aspects. This study explores the potential of a mobile LiDAR system for precise detection and size estimation, augmented by a GNSS receiver for localization, to develop a robust pothole surveillance system. A four-step framework is proposed: LiDAR data processing to generate cross-sectional images, training of a deep learning object detection network, aggregation of inferences for final decision-making, and synchronization with GNSS locations to create inspection maps. Validation using unseen road strips with varied pothole sizes and shapes demonstrated the system's effectiveness and accuracy. By introducing a novel framework and integrating it into an end-to-end pothole detection system, this research advances LiDAR-based inspection methods, promising to enhance pothole maintenance efficiency and road user safety.

In the study by Wenming Cao (2020), the focus lies on the critical task of detecting cracks in road pavements, which is essential for effective maintenance and ensuring traffic safety. The research area is delineated into three main categories: image processing, machine learning, and 3D imaging-based methods.Image processing algorithms such as threshold segmentation, edge detection, and region growing are employed to analyze images and identify crack features. Traditional machine learning techniques like neural networks and support vector machines rely on handcrafted features derived from image processing. However, the advent of deep learning has revolutionized crack detection by utilizing neural networks, leading to significant improvements in detection performance. The study delves into a comparative analysis of deep learning neural networks utilized in crack detection across three main approaches: classification-based, object detection-based, and segmentation-based methods. Evaluation metrics and performance on benchmark datasets are thoroughly examined to provide insights into the effectiveness of each approach. Moreover, with the advancements in 3D technology, crack detection using 3D data has emerged as a new research frontier. The paper compares different types of 3D data representations and evaluates the performance of deep neural networks for 3D object detection. Additionally, it comprehensively reviews traditional and deep learning-based crack detection methods utilizing 3D data. Overall, the study offers valuable insights into the evolution and comparison of various crack detection methodologies, emphasizing the transformative impact of deep learning and 3D imaging technologies in this field.

Garande (2024) highlights the limitations of traditional road inspections, emphasizing their manual nature, susceptibility to human error, and inefficiencies. To address these challenges, the paper introduces a novel approach for automated roadway inspection utilizing a Convolutional Neural Network (CNN) model.The proposed system employs computer vision techniques to detect potholes and speed breakers on road surfaces from images. A CNN model was developed and trained on a diverse dataset of road images encompassing various types of potholes and speed breakers, along with different lighting conditions and road backgrounds. The results indicate that the CNN model achieved an impressive accuracy rate of 93% in detecting these road defects, showcasing the efficacy of deep learning for automated roadway inspections. This automated system holds the potential to significantly enhance the efficiency and objectivity of road inspections, ultimately leading to expedited repairs and improved road safety. (Pandey et al 2022)The economic and social prosperity of modern society depends on a well-built and maintained transportation system. Due to lack of funding, inadequate budgetary allocations, and ever-increasing traffic, highway maintenance presents substantial challenges. Finding and fixing potholes in the road in a timely manner is essential to maintaining a crucial, safe road infrastructure.The current methods for detecting potholes are inaccurate and slow to infer, requiring a tedious physical assessment of the roadways. In order to detect potholes, this paper suggests a novel use of convolutional neural networks on accelerometer data. Data is gathered using an iOS smartphone running a specific application that is mounted on a car's dashboard.According to the experimental findings, the suggested CNN method for pothole identification offers a considerable gain over the current approaches in terms of accuracy and computing complexity. (Reddy et al 2022) Potholes are caused by aging roadways and inadequate road maintenance programs, and their quantity grows over time. Potholes endanger both the effectiveness of transportation and road safety. Furthermore, they frequently play a part in auto accidents. It is imperative to promptly ascertain the locations and sizes of potholes in order to remedy the issues they cause. A pothole database can be used to create sophisticated road maintenance plans, but first it needs to be equipped with a pothole-detection system that can gather data on potholes over a large region and at a reasonable cost. But manual detection has long been the norm for pothole repair. Due to the unreliable detection of vibration-based methods and the high cost of laser scanning-based methods, recent automatic detection systems, such as those based on vibrations or scanning, are inadequate to accurately and economically identify potholes. Therefore, we provide a novel pothole-detection method in this study that makes use of a retail black-box camera. The suggested method finds potholes inexpensively and over a large area. Our team has created an innovative pothole-detection algorithm that is tailored to operate in the embedded computer environments seen in black-box cameras. We provide experimental results using our suggested method, demonstrating the accurate and real-time detection of potholes.

This(Tamagusko 2023) work assesses You Only Look Once (YOLO) models for object detection (OD) on a dataset of 665 photos of road pavement tagged with potholes. Using transfer learning approaches, the models—including YOLO versions 3, 4, and 5—were modified for pothole detection. The results showed that YOLOv4 had the highest mean average precision, and that YOLOv4-tiny had the best decreased inference time, which made it the best choice for mobile applications. YOLOv5s showed promise in terms of scalability and ease of implementation.

This study (Goswami et al 2023) aims to develop a machine learning model that can instantly identify potholes in roads, a major cause of accidents. The model uses the You Only Look Once (YOLO) version 7 object detection algorithm, with a precision and recall of 0.94 and 0.98, respectively. The system can identify potholes in both bright and dim environments in real-time.

In this research (Gujar et al 2024), a specially trained machine learning model for real-time pothole detection on roads is created and evaluated. One of the main reasons for accidents that happen every year is potholes and road craters. In this study, we conduct a comparison analysis to select a suitable object detection algorithm, and You Only Look Once (YOLO) version 8 is the selected algorithm. Through model training on a customized dataset, our method obtains a mean Average Precision (mAP) of 95.82%, a precision of 0.95, and a recall value of 0.97. Improving traffic safety protocols is an urgent issue, and the proposed method performs well in real-time pothole detection in both well-lit and low-light conditions.

(Prakash and Sri 2022)A pothole identification model for India has been trained and analyzed using the YOLOX object detection method. With a total size of 7.22 MB, the model with a pothole dataset training got an Average Precision (AP) value of 85.6%. This is the first trial of the YOLOX algorithm for pothole detection, which lowers expenses and speeds up the process. The goal of the project is to lower pothole identification expenses and enhance road maintenance.

(Saurabh Pehere,.et al 2020) and (Surekha 2020) Particularly in India, potholes on the road can result in expensive damage and serious accidents. Methods for remote sensing are being developed to increase the effectiveness of pavement inspections. Unmanned aerial vehicle (UAV) photographs of pavement are used to differentiate pavements with pothole patterns from those without. The approach combines live road footage with straightforward image processing techniques like edge detection and medium filter. The technique yielded a 74.4% recall rate and an 80% precision rate. Road maintenance and monitoring can be improved even more by cutting-edge technologies like artificial intelligence and machine learning.

(Ali. R. G et al. 2021) Says the Potholes are essential for preserving the longevity and robustness of roads and highways, resulting in mishaps and monetary damages. To identify and categorize pothole regions in photos of asphalt pavement, a deep learning approach has been put forth. RetinaNet is used in the process to generate bounding boxes, and Conditional Random Fields are used for segmentation. The methodology comprises segmentation, localization, and image preprocessing; the findings demonstrate that potholes are accurately located with an accuracy of 93.04%. Results with Conditional Random Fields are also favourable.

2.3 Impact of Weather Conditions on Pothole Detection

2.3.1 Seasonal Variations in Pothole Formation

Weather conditions, particularly freeze-thaw events, have significant implications for pavement systems. Recent climate changes have raised concerns about their impact on freeze-thaw cycles, yet this aspect remains understudied. Masrur et al. (2022) quantified the frequency of freeze-thaw events at various depths within pavement systems. They observed notable decreases in such events at shallower depths during early and late winter months, although annual occurrences at the air temperature sensor level appeared randomly distributed throughout the analysis period.

2.3.2 Climate Change Adaptation for Porous Asphalt Roads

This section examines the influence of climate change on porous asphalt (PA) roads, focusing on winter weather conditions characterized by freeze-thaw cycles and resultant road damage. Kwiatkowski et al. (2016) highlight the threat posed by changes in weather patterns to the serviceability and long-term performance of PA pavements. They emphasize the need to understand the regional impact of climate change on specific road types, given that up to half of road maintenance costs are attributed to weather stresses. The chapter explores the correlation between historic winter weather patterns and PA pavement performance, particularly sensitive to freezing/thawing phenomena. India's death rate due to potholes is about 30% annually. These depressions, found in every kilometer of roads, are mainly formed during the rainy season and pose a significant risk. The Ministry of Road Transport and Highways lacks a system to track potholes, so the PDS-Pothole Detection System was developed. The system uses video input, Raspberry-Pi processing, and GPS to identify potholes, with accuracy levels exceeding 80 percent. (Yash et al 2023).

2.3.3 Effects of Weather Conditions on Image Quality

Adverse weather conditions like haze and snowfall present challenges for maintaining high-quality image capture and affect the effectiveness of drone detection systems. Consequently, identifying and locating targets becomes more difficult in adverse weather scenarios (Wenxuan Fang et al., 2023).

Moreover, the development of autonomous vehicles and intelligent driver assistance systems has garnered significant attention, yet their performance suffers under adverse weather conditions such as rain, snow, fog, and hail. Despite this, there is currently no comprehensive review addressing the impact of weather on the various sensor types utilized in autonomous vehicles (Shizhe Zang et al., 2019).

Unmanned Aerial Vehicle (UAV) detection in real-time is a burgeoning field, leveraging computer vision and deep learning algorithms. However, concerns have arisen regarding the potential risks and misuse associated with the widespread use of UAVs in various applications. This study aims to detect UAVs under adverse weather conditions, such as rain, and image distortions like motion blur and noise. The objective is to assess how these adverse conditions impact UAV detection performance and propose techniques to enhance model robustness.To achieve this goal, a custom training dataset was curated by amalgamating multiple existing datasets and enriching them with complex backgrounds. Additionally, a custom testing dataset containing UAV images affected by adverse conditions was generated. The performance of prominent object detection algorithms, including YOLOv5, YOLOv8, Faster-RCNN, RetinaNet, and YOLO-NAS, was evaluated on the proposed dataset.Results revealed a significant performance decrease under adverse conditions compared to clean images. However, training the models on the augmented dataset, which included samples of distorted and weather-affected images, substantially improved performance under challenging settings. These findings underscore the importance of considering adverse weather conditions during model training and emphasize the significance of data enrichment for enhancing model generalization.Furthermore, the study highlights the necessity for further research into advanced techniques and architectures to ensure reliable UAV detection under extreme weather conditions and image distortions (Munir et al., 2023).

2.3.4 Influence of Weather Factors on Pothole Visibility

Potholes present a formidable obstacle to road safety and infrastructure integrity, posing threats not only to vehicles but also to pedestrians navigating these thoroughfares. The imperative to detect potholes swiftly and accurately, particularly amidst fluctuating lighting conditions, cannot be overstated, given its paramount importance in safeguarding road users and expeditiously rectifying these perilous road imperfections. The ubiquity of cameras on vehicles and smartphones has spurred burgeoning interest in harnessing the power of computer vision methodologies for pothole detection, signaling a promising avenue for mitigating this pervasive roadway hazard (Jakubec et al., 2023).

The detection of potholes stands as a linchpin in the realm of road safety and maintenance, necessitating proactive measures to address these surface irregularities promptly. Stemming from the interplay of heavy traffic and inclement weather, potholes pose tangible risks to vehicular integrity and safety, underscoring the critical need for vigilant detection and remediation efforts. Autonomous vehicles, in particular, rely on robust pothole detection systems to navigate roadways effectively. However, the efficacy of such systems may be hampered by adverse weather conditions and suboptimal lighting, warranting innovative strategies to bolster their performance and resilience in adverse environmental conditions (Frnda et al., 2024).

Road irregularities like potholes and cracks are frequently encountered throughout our daily commutes and travels. Owners of all kinds of vehicles have always been concerned about the expense of repairing damage brought on by potholes. Therefore, early detection procedures can aid in prompt road maintenance service response and the avoidance of accidents caused by potholes. In this work, the computer vision model library You Look Only Once version 3, or Yolo v3, is used to automatically detect potholes. Our capacity to notice road damage is naturally impacted by weather and light conditions when driving. Visual object detectors are likewise adversely affected by such unfavourable situations. This study looked at how unfavourable circumstances affect pothole spotting. Thus, the two primary components of this study's basic design are as follows, (1) the creation and processing of the dataset and (2) the dataset experiments conducted with Yolo v3. Furthermore, we included Sparse R-CNN in our experiments. For this goal, a dataset consisting of subsets of photos captured under varying light and weather was generated. To the best of our knowledge, there exists no extensive analysis of pothole detecting performance under adverse conditions. Yolo v3 is still a competitive design that delivers good results with lower hardware requirements, even with the availability of newer libraries. (Buˇcko et al 2022)

Road distress in India is increasing due to climate change, heavy rains, and conventional road construction methods. In 2017, there was a 50% increase in road accidents due to pothole-related issues. To address this, a study aims to develop rapid pothole detection techniques using remote sensing and GIS techniques. Data is collected using ODK Collect and analysed in QGIS software, while volume is calculated using Autocad software. This approach ensures time-saving pothole detection and cost optimization through optimal budget estimation of repair materials. (Yadav et al 2019).

2.4 Super-Resolution Algorithms for Image Refinement

Reconstructing High-Resolution (HR) images from one or more Low-Resolution (LR) images is known as Image Super-Resolution (SR) approach. An extensive analysis of image super-resolution techniques is presented in this publication. There are thorough descriptions of the various types of image resolution as well as the Image Super-Resolution technique. A thorough explanation of several SR approaches is provided, along with an explanation of some pertinent SR techniques. Additionally, a comparison and qualitative and quantitative performance evaluation of different SR approaches are provided in this work. (Vishnu Kumar 2016).

2.4.1 Overview of Super-Resolution Techniques

This paper provides an overview of the various research papers related to the research topic described before. Picture One of the most significant areas of image processing study is super resolution. The term "super resolution image" describes a method of creating a high-resolution image from one or more low-quality photographs. Super-Resolution (SR) is essentially the process of fusing together a series of noisy, blurry low-resolution (LR) images to produce a higher resolution (HR) image. For super resolution, which is an image restoration and noise reduction procedure. The resolution techniques that have been employed thus far can be categorized into three groups: wavelet domain techniques, spatial domain techniques, and frequency-domain techniques (Teraiya 2016).

Super-resolution algorithms play a crucial role in refining images, providing the technical backbone for various intelligent devices used in target tracking and detection. However, enhancing image resolution typically involves significant additional costs during the image acquisition stage (Qing Kuang, 2021).

The advancement of satellite image processing technology has led to a wider usage of remote sensing images in real-world scenarios. However, current remote sensing imaging technology often struggles to meet application requirements due to limitations and external environmental factors, resulting in low-resolution images. To address this issue, image super-resolution methods are increasingly being applied to recover and reconstruct remote sensing images. These methods overcome limitations in image acquisition systems and environments, improving image quality and resolving issues such as blurred regions of interest. Recent progress in image super-resolution methods, fuelled by the continuous development of deep learning algorithms, has significantly advanced the field of image processing (Xuan Wang, 2022).

Image super-resolution has emerged as a critical technology, particularly in the medical and industrial sectors. Consequently, substantial efforts have been dedicated to the development of image super-resolution algorithms (Yoong Khang Ooi et al, 2021).

Image super-resolution technology involves creating high-resolution photographs from low-resolution images. Deep learning advancements have led to the development of deep learning-based image super-resolution technologies The study offers a deep learning-based system for pothole early identification using images and videos, lowering the risk of accidents caused by the problem of potholes on roads and highways across the globe.(Seetha and Prasanna 2023)

2.4.2 Application of SR Algorithms in Aerial Image Processing

In the realm of aerial image processing, the integration of Super-Resolution (SR) algorithms has emerged as a promising avenue to bolster the accuracy of pothole object detection. Researchers have pioneered various object detection methodologies fortified with SR techniques, aimed at generating enhanced images from low-resolution inputs prior to conducting object detection tasks (Salaudeen, 2022). This innovative approach holds tremendous potential for elevating the precision and reliability of pothole detection systems, thereby contributing to enhanced road safety and infrastructure maintenance efforts.

Moreover, SR algorithms play a pivotal role in several remote sensing applications, offering effective solutions to address inherent limitations in image resolution. By leveraging SR techniques to augment the spatial resolution of imaging systems, researchers can magnify minute details within images, thereby facilitating more nuanced analyses and interpretations. Notably, unlike conventional resolution enhancement methods, SR methodologies circumvent common pitfalls such as noise introduction, spectral distortion, and the degradation of image clarity, thereby enhancing the overall quality and fidelity of remote sensing data (Rohith et al, 2021).

Furthermore, the proliferation of smartphones as primary cameras on drones has catalyzed a surge in algorithmic developments aimed at refining images captured by these versatile devices. Despite the commendable strides made in achieving high-resolution imagery with cutting-edge drone cameras, challenges persist due to the formidable computational burden associated with processing vast quantities of pixels and capturing images from diverse perspectives for stereo-view applications. These challenges underscore the pressing need for continued innovation and refinement in algorithmic approaches to optimize the performance and efficacy of drone-based imaging systems, particularly in the context of pothole detection and infrastructure monitoring endeavours.

2.4.3 Comparative Analysis of SR Methods

This section conducts a comparative analysis of various super-resolution techniques, focusing on factors like computational complexity, reconstruction accuracy, and suitability for UAV-based pothole detection tasks.

In recent years, there has been significant progress in the development of image super-resolution (SR) techniques, particularly leveraging convolutional neural networks (CNNs). However, blindly increasing the depth of CNNs does not necessarily lead to improved performance and may introduce additional training challenges. To address this, a lightweight image super-resolution reconstruction algorithm (SISR-RFDM) is proposed in this paper. This algorithm is based on the residual feature distillation mechanism (RFDM), which enhances the network's ability to recover high-frequency details such as edges and textures. The proposed algorithm incorporates spatial attention (SA) modules to provide informative cues for detail recovery and introduces global feature fusion (GFF) to enhance inter-layer information flow and feature reuse. Finally, all these features are utilized in the reconstruction module to generate high-quality images. Experimental results demonstrate that the proposed algorithm outperforms other comparative algorithms in terms of both subjective visual effects and objective evaluation quality (Zihan Yu 2024).

This paper delves into the intricate landscape of 3D reconstruction methods in computer vision, particularly focusing on the evolution propelled by deep learning techniques. It underscores the significance of these advancements, showcasing their heightened adaptability and efficiency when juxtaposed with conventional approaches. By segmenting these methods according to the representation of 3D models, the paper not only offers a comprehensive overview but also navigates through diverse frameworks tailored for 3D reconstruction, elucidating their distinct nuances and applications within the realm of deep learning (Yuanchun Wang 2023).

Potholes are typical street hazards that cause damage to cars and put drivers in danger. Convolutional neural networks (CNNs) are widely used in the business to recognize objects based on deep learning methodologies. This has led to significant advancements in programming and equipment upgrades. This work presents a novel and improved calculation to support the use of low-goal cameras or low-goal images and video feed for Super Goal (SR) through Super Goal Generative Ill-disposed Networks (SRGANs)-based programmed pothole recognition. Next, we've carried out a gauge pothole finding execution on both high-quality and low-quality dash cam images using an organization called You Just Look Once (Consequences be damned), more precisely the YOLOv7 organization. Next, we've demonstrated and investigated the increase in speed and accuracy over the benchmark following the use of upscaling on the low-quality photos (Rout, N. K et al 2023).

Road hazards such as potholes have been identified as the main cause of car damage and accidents. The current state of the roadways is flawed due to excessive rainfall and inadequate infrastructure. Finding the potholes by hand takes time and is not a perfect way to find the fault. The purpose of the suggested approach is to identify potholes on muddy roads and in photos of highways to prevent accidents and car damage. To identify whether the roads are pothole-filled or plain, deep learning techniques are employed to classify a picture collection. Pictures are gathered from online resources, one from Kaggle (muddy roads) dataset and another from the internet (highway roads) dataset. The model is trained using pre-trained models Resnet50, Inception V2, and VGG19. The implementation of a web application tests the model's ability to distinguish between roads with potholes and those without, using pre-selected models such as Resnet50, Inception ResNet V2, and VGG19 models that have been trained for the system.An analysis is conducted on the model performances to improve accuracy, precision, and recall.Contrast with the IncipetionResNetV2 and Resnet50 models.With 97 percent accuracy on interstate roads and 98 percent accuracy on muddy roads, the VGG19 model has produced the best results.(Saisree et al 2023)

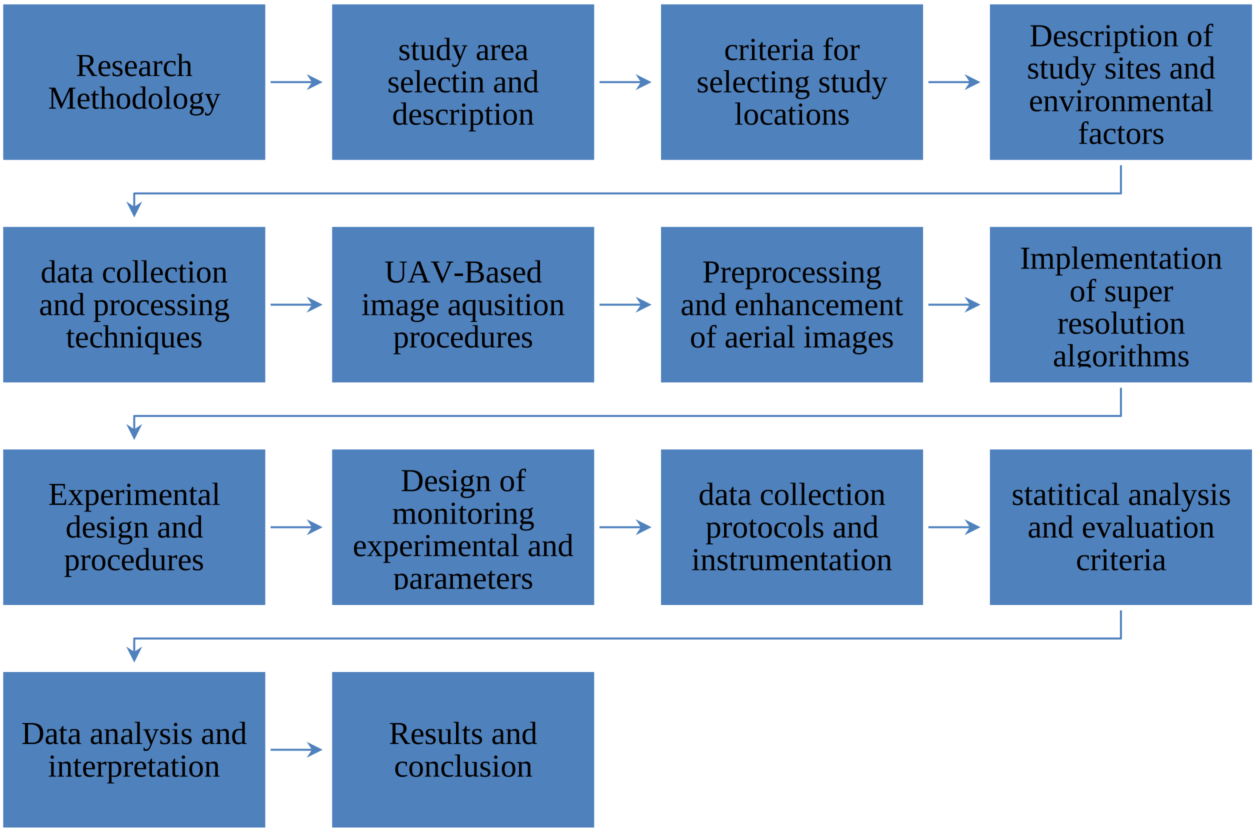
Recovery of high-resolution images from comparable Low-Resolution (LR) copies is the goal of Single Image Super Resolution (SISR) reconstruction, which is fundamentally an ill-posed inverse problem. Learning-based approaches, which show promise in terms of computation performance and efficiency, have been widely used in recent years to address this issue. This is particularly true for deep neural network-based picture sharpening processing. Two broad categories of learning-based approaches are deep learning-based approaches and conventional methods. Convolutional neural networks (CNN) and generative adversarial networks (GAN), which are based on internal network structure, are two deep learning-based picture super-resolution techniques that will be reviewed in this survey. In addition, this study outlines the practical sectors in which single-frame image super resolution is employed. Furthermore, some avenues for future study on picture super resolution methods are noted (liu et al 2021).

The primary loss in picture resolution improvement is the high frequency content (edges) of the image. Therefore, maintaining the edges is essential to improving the image quality. The discrete wavelet transforms (DWT), stationary wavelet transform (SWT), dual tree complex wavelet transform (DT-CWT), wavelet zero padding (WZP), cycle spinning (CS), Vector-Valued Image Regularization with Partial Differential Equations (VVIR-PDE), and Inter Subband Correlation Technique (ISC) are some of the image resolution enhancement techniques that are compared in this paper. (Patel 2015)

Furthermore, a meticulous comparative analysis is meticulously conducted, scrutinizing an array of methodologies devised for pothole detection leveraging Unmanned Aerial Vehicles (UAVs). Through a holistic assessment encompassing factors like precision, computational efficiency, and practical applicability, the study renders invaluable insights into the optimal techniques tailored for the detection of potholes from aerial imagery. This comparative exploration serves as a beacon guiding researchers and practitioners towards the most effective strategies in addressing this critical aspect of road infrastructure maintenance and safety.

Chapter 3

3. Research Methodology



3.1 Study Area Selection and Description

The choice of study area and its description are crucial since they set the stage for the whole research project. Researchers can make sure that their data collection efforts are concentrated on places that are most relevant to their research aims by establishing explicit criteria for choosing study locations. Furthermore, thorough descriptions of study locations facilitate a deeper comprehension of the contextual elements affecting the phenomena under investigation. All things considered, this stage guarantees that the study is carried out in an organized and knowledgeable manner, producing solid and trustworthy results.

3.1.1 Criteria for Selecting Study Locations

1. **Features of the Road Network**

This criterion entails taking into account the several kinds of roads found in the study area, including rural roads, urban streets, and highways. Different road kinds have different features, such as pavement types, building techniques, and upkeep procedures. Researchers can evaluate how various infrastructural conditions affect pothole formation, severity, and maintenance requirements by considering a varied range of road types. Pothole frequency and distribution can be influenced by factors such as higher traffic volumes and faster deterioration rates on urban roads relative to rural roads.

2. **Volume of Traffic:**

The volume of vehicles on the roadways in the studied areas is referred to as traffic volume. Roads with heavy traffic often see increased wear and tear, which accelerates pavement deterioration and causes potholes to appear more frequently. On the other hand, various pothole patterns may be seen on low-traffic roads due to variables like vehicle weight distribution, speed, and maintenance frequency. By incorporating study sites with different levels of traffic, researchers can determine how vehicle load affects the formation of potholes and gauge how well pavement management techniques work.

3. **Diversity by Region:**

Choosing research sites that reflect various geographic regions, topographies, and environmental circumstances is necessary to provide geographic variety. The formation of potholes and the functionality of road infrastructure can be impacted by various factors, including topography, vegetation cover, soil composition, and climate. For example, the expansion and contraction of pavement materials may cause more significant pothole damage in areas with harsh winters and frequent freeze-thaw cycles. Through the integration of study sites across several geographic regions, scientists may detect fluctuations in environmental parameters and evaluate their influence on pothole dynamics.

4. **Safety and Accessibility:**

In order to make sure that the study places selected are both practicable and safe for carrying out research activities, accessibility and safety concerns are essential. Sites that are convenient for researchers, equipment, and UAV operations reduce logistical obstacles and enable effective data collecting. In order to avoid mishaps and injuries, it is also crucial to guarantee safety when conducting fieldwork. Before choosing study locations, researchers must evaluate potential risks such as traffic congestion, road barriers, and unfavourable weather. Researchers can reduce dangers connected with fieldwork and expedite data gathering by giving accessibility and safety-first priority.

3.1.2 Description of Study Sites and Environmental Factors

Pavement conditions and environmental elements affecting infrastructure are studied at Gustave Eiffel University, which is located at roughly 48.8397° N latitude and 2.5867° E longitude. The study site and its environmental context are explained in detail below.

1. **Geographic Coordinates:** A precise location reference is provided by the university's geographic coordinates, which is essential for mapping and spatial analysis. Coordinates for latitude and longitude, like those for Gustave Eiffel University, are the foundation for gathering and analyzing geospatial data, which enables researchers to precisely identify study locations and track evolution over time.
2. **Pavement Types:** There are several different types of pavements on the campus, such as asphalt, concrete, and maybe other composite materials. Every form of pavement has distinct qualities, including resilience to weathering and traffic loads, surface roughness, and durability. It is crucial to comprehend the makeup and state of these pavements in order to evaluate their effectiveness and set maintenance priorities. For instance, asphalt pavements may eventually be prone to rutting and surface degradation, whereas concrete pavements may withstand high traffic better but crack in freezing weather.

Pavement Type	Material Composition	Key Characteristics	Common Distress Patterns
Concrete	Cement, Aggregate	Durable, Rigid	Cracking, Spalling
Asphalt	Bitumen, Aggregate	Flexible, Smooth	Rutting, Potholes
Composite	Various Materials	Varies	Dependent on Materials

Table 1 Shows The Pavement Types And Their Specifications

3. **Prevailing Environmental Conditions:** A variety of elements that may have an impact on the integrity and health of the pavement can be found in the Gustave Eiffel University's surroundings.
4. **Temperature:** Seasonal and diurnal variations in temperature can cause pavement materials to expand and contract, which over time can cause cracking and damage. Severe weather, including cycles of freezing and thawing, can make these impacts worse.
5. **Humidity:** Excessive humidity can hasten the entry of moisture into pavement layers,

weakening the underlying structure and encouraging the development of cracks and potholes. Prolonged moisture exposure can also lead to surface erosion and pavement integrity degradation.

6. **Precipitation:** Through surface runoff, erosion, and moisture infiltration, rainfall and precipitation events can have a direct effect on pavement surfaces. Pavement deterioration can be accelerated by water accumulation in cracks and potholes, especially in places with inadequate drainage.
7. **Sunlight Exposure:** Over time, UV radiation from sunshine can deteriorate pavement materials, resulting in fading, surface oxidation, and structural integrity loss. Pavements exposed to extended sunshine without sufficient protective coatings may suffer from surface degradation and hastened disintegration.
8. **Vehicle Traffic:** Over time, wear and fatigue on pavement surfaces can result from the volume and variety of automobile traffic that travels throughout university campuses. The development of potholes and surface distress, as well as the rate of pavement deterioration, can be influenced by variables such vehicle weight, speed, and frequency of use.
9. **Maintenance Activities:** Routine duties like patching, sealing, and sweeping can have an impact on the lifespan and condition of pavement. Pavement service life can be increased and environmental consequences can be lessened with the use of proper maintenance techniques.

To effectively maintain infrastructure assets and develop maintenance programs, it is imperative to comprehend the ways in which various environmental elements interact with pavement materials and design. In order to make informed decisions and allocate resources for infrastructure management, researchers can find trends, patterns, and risk factors by methodically collecting and evaluating data on pavement state in conjunction with environmental conditions.

Factor	Description	Impact on Pavement
Temperature	Average Range: -2°C (winter) to 35°C (summer)	Expansion and Contraction, Cracking
Humidity	Average Humidity: 60-80%	Moisture Infiltration, Weakening
Precipitation	Average Annual Rainfall: 650 mm	Surface Runoff, Erosion, Potholes
Sunlight	Average Sunlight Hours: 2,000 Hours/Year	UV Degradation, Surface Fading

Table 2 Shows The Weather Conditions

Figure 1: Pothole

3.2 Data Collection and Processing Techniques

3.2.1 UAV-Based Image Acquisition Procedures

Gustave Eiffel University uses dji matrice 300 rtk drone to capture aerial photographs of water-filled potholes. A methodical approach is taken to guarantee high-quality data collection and precise 3D reconstruction. This requires a few crucial steps.

1. **Aircraft Scheduling**

Ensuring thorough coverage of the research area with adequate picture overlap for precise photogrammetric analysis is the main goal of flight planning. With the UAV flown at a precise height of 3.36 meters, 1.08 mm/pixel of ground resolution is possible. This exact height facilitates the taking of finely detailed photos, which are essential for identifying small-scale irregularities in the road surface, such as potholes. Each flight has a covering area of 118 m², guaranteeing a comprehensive mapping of the research location.

2. **Picture Overlap**

A considerable amount of picture overlap. Roughly 80% on both the front and side Is maintained in order to close data gaps and facilitate seamless 3D reconstruction. Whereas the side overlap describes the overlap between neighbouring flight paths, Front overlap describes the overlap between consecutive photographs taken along the flight path. For precise 3D modelling, this redundancy makes sure that every area of the ground is recorded several times from various viewpoints.

3. **Flight Path Planning**

Over the research area, the UAV's flight route is precisely plotted to match a grid pattern. Systematic coverage and consistent overlap are ensured by the grid. These pathways are created using sophisticated flight planning software, which optimizes the mission by accounting for abstractions Wind and battery life.

4. **Camera Settings and Image Capturing Strategies**

To take high-quality images, the UAV's camera settings must be configured. With a fixed focal length of 4.5 mm, the camera is configured to record photos at a resolution of 4056 x 3040 pixels.

5. **Camera Calibration**

To guarantee clear, high-quality images in a range of lighting situations, exposure settings calibration is essential.to prevent Over exposure or under exposure, the ISO, shutter speed and aperture must be adjusted.

6. **Number of Images and Stations**

48 camera stations are used to carry out the flight plan, and each station takes 48 pictures to guarantee sufficient overlap for photographic reconstruction. The large number of photos collected guarantees that all relevant data points are recorded, improving the 3D models accuracy and level of detail.

7. **Real Time Monitoring.**

During an operation, real time flight monitoring enables quick adjustments to respond to shifting impediments or environmental circumstances, resulting in the best possible photographs being taken. These Entails use ground control software to monitor the position camera,Status and surrounding conditions of the UAV.

8. **Data Management**

As soon as the photos are taken, they are reviewed for accuracy and comprehensiveness. For assistance during the processing stage,Metadata is stored, such as GPS coordinates, camera settings and timestamps.

The section describes the meticulous preparation and exact technological configurations needed for UAV based image capture in order to guarantee detailed, high quality data gathering for precise photogrammetric analysis and three dimensional reconstruction. As shown in figure 2, high picture overlap is maintained to enhance the accuracy of the 3D model generated from the Photos. Real-time Flight monitoring allows for fast adjustments in response to changing impediments or environmental conditions, ensuring that the best possible photos are taken during the operation. High picture overlap under real time flight monitoring or crucial components for collecting the finest possible photographs, compensating for shifting environmental circumstances and impediments.

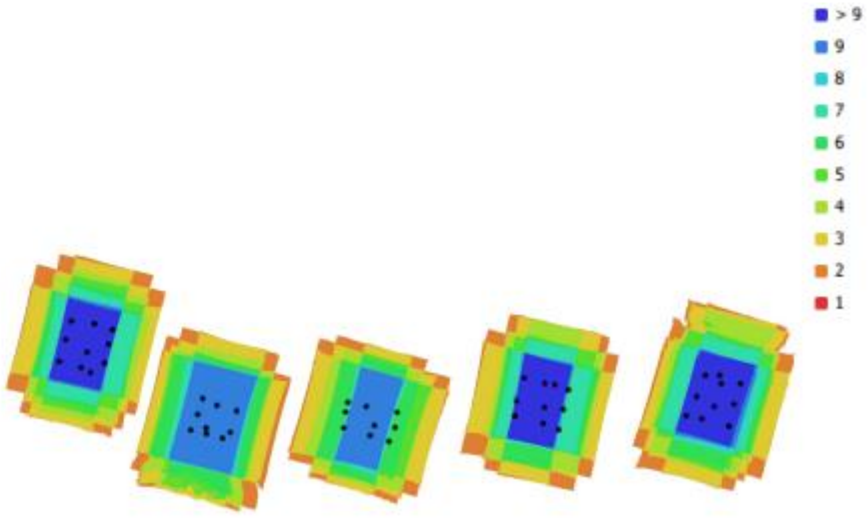


Figure 2: Camera Locations And Image Overlap.

Parameter	Specification
Number of Images	48
Flying Altitude	3.36 m
Ground Resolution	1.08 mm/pix
Coverage Area	118 m^2
Camera Stations	48
Tie Points	65,361
Projections	292,135
Reprojection Error	1.01 pix
Camera Model	ZH20 (4.5mm)
Resolution	4056 x 3040
Focal Length	4.5 mm
Pixel Size	1.6 x 1.6 µm
Precalibrated	No

Table 3 Technical Specifications And Performance Of Cameras

3.2.2 Preprocessing and Enhancement of Aerial Images

Preprocessing techniques are used to raw aerial photos obtained from dji matrice 300 rtk drone in order to enhance their accuracy and quality. These actions consist of

1. **Georeferencing**

To provide a spatial reference, georeferencing entails lining up the aerial photos with geographic coordinates. The accuracy of the photographs' placement on the surface of the Earth is guaranteed by this procedure. Accurate mapping and spatial analysis are made possible by georeferencing, which provides each pixel in the image with a geographic coordinate. The georeferencing procedure is shown in Fig. 3, which also shows how aerial photos are matched to geographic locations.

2. **Orthorectification**

The process of orthorectification produces orthorectified pictures by adjusting the aerial photographs for perspective distortion and geographical variances. With this adjustment, the photos will precisely depict the Earth's surface, free from distortions brought on by the geography of the area or the viewing angle of the sensor. For accurate measurement and analysis of ground characteristics, orthorectified pictures are necessary. The orthorectification procedure is shown in Fig. 4, which shows how perspective distortion is fixed to provide realistic depictions of the landscape.

3. **Radiometric Correction**

To accommodate for differences in illumination conditions and sensor attributes, radiometric correction entails altering the pixel values in the aerial photographs. By ensuring uniformity in brightness and colour throughout the pictures, this correction qualifies them for quantitative study and comparison. The interpretability and accuracy of the pictures are enhanced by radiometric correction, which eliminates artifacts resulting from variations in light and sensor response. The radiometric correction procedure is shown in Fig. 5, where the pixel values are adjusted to get consistent brightness and colour.

To prepare unprocessed aerial photos for additional study and interpretation, several preprocessing procedures are crucial. The processes of georeferencing, orthorectification, and radiometric correction guarantee that the pictures faithfully depict the surface of the Earth and offer trustworthy data for a range of uses, including infrastructure appraisal, land use planning, and environmental monitoring.

3.2.3 Using Algorithms for Super-Resolution

Advanced super-resolution methods are applied utilizing Agisoft Metashape pro software and Digital Elevation Models (DEM) to improve the sharpness and resolution of aerial photographs.

1. **Algorithm Selection**

Agisoft Metashape pro software was carefully selected for the study because of its remarkable photographer and image processing capabilities. Renowned for its cutting-edge algorithms, Agisoft Metashape pro software makes it easier to extract geographic information from 2D photos so that the 3D buildings can be precisely recreated. The program is a great fit for this activity because of its strong processing capacity and ability to handle massive data sets.

2. **Motives Behind the Selection**

A. Photogrammetric Proficiency

Because the edges of the meta ship were created with photographic applications in mind. It excels at accurately transforming 2D photos into 3D models. Its complex algorithms examine collections of images to find type points that produce dense point clouds, both necessary for precise 3D reconstructions,

B. Handling Big data Sets

Edges of meta shapes capacity to effectively handle large data sets is essential for our research. The software's ability to handle and analyze massive volumes of data guarantees that no information is missed throughout the reconstruction process, especially considering the high-resolution photos taken by dji matrice 300 rtk drone.

C. Detailed Reconstructions

Agisoft Metashape pro software is an excellent tool for creating very accurate and detailed 3D models. Because of its sophisticated image processing capabilities, it is possible to generate extremely accurate textures and meshes, which are essential for recognizing and examining minute details like potholes in road surfaces.

E. Geometric Accuracy

One of the software's main benefits is its capacity To produce models with precise geometric details in order to guarantee that their special relationships between image points are maintained and produced models that faithfully depict the real world scene. Agisoft Metashape pro software uses strict algorithms.

F. User Friendly Interface

Agisoft Metashape pro software has a straightforward interface that makes it easier for users to deal with it, even with its sophisticated capabilities, because of its accessibility even the most difficult photogrammetric jobs can be completed effectively and without the need for specialised knowledge for training.

G. Versatility and Integration

Adoption easily interfaces with other software tools used in GIS and 3D modelling. And it is comfortable with a wide range of data types. A Seamless process is made possible by this adaptability from data collection to final analysis and presentation.

3. Parameter Optimization:

Adjusting various Agisoft Metashape pro software settings is what parameter optimization entails in order to improve the quality of the 3D models That are generated. Important parameters are overlapping percentage, which guarantees sufficient data points for precise reconstruction And mesh quality settings, which strike a compromise between computational efficiency and detail level.For sophisticated 3D models, high overlap percentage, typically 80 % allows for improved image alignment and dense point cloud production (Inzerillo, L., Acuto, F., Pisciotta, A., Dunn, I.,2023). Furthermore, precise elevation models are ensured by the optimization of resolution and interpolation techniques for the generation of digital elevation models (DEM), which aid in the deduction of surface depressions and potholes to improve overall model quality and reliability. Adjustments are also made to the parameters pertaining to camera calibration, Tie point position and dense cloud creation. The ideal parameters are found via interactive testing and validation, guarantee high fidelity, 3D Reconstructions without using excessive amounts of processing power

4. Implementation Procedure Preprocessing

Georeferencing and orthorectification are applied to the raw photos that the dji matrice 300 rtk drone took during this phase. In order to ensure precise spatial alignment with real-world locations, georeferencing entails adding geographic coordinates to the photographs. Images with uniform size and little geometric distortion are produced via orthorectification, which corrects for perspective distortions brought on by changes in landscape elevation. These preprocessing procedures are necessary to guarantee that the real spatial connections and dimensions of the research area are appropriately reflected in any future analysis.

5. DEM Generation

Advanced algorithms and procedures are used to create a digital elevation model. DEM from processed photos with the goal of accurately capturing specific elevation information. The resolution and precision of elevation models are improved by advanced DEM generating techniques like stereopair matching and LiDAR data integration, which make it possible to detect minute surface irregularities like potholes. Positional and elevation errors can be quantified and insights into the dependability of DEM data can be gained using error modelling and uncertainty quantification techniques. Additionally, different elevation sources are combined using DEM fusion techniques, such weighted averaging or geostatistical interpolation to create a comprehensive picture of the landscape.

6. 3D Model Reconstruction

Agisoft Metashape pro software uses a complex procedure that makes use of pre-processed pictures and the resulting digital elevation model (DEM) to create a high-resolution 3D model of the study area. To begin a dense point cloud is created by reconstructing individual points in three dimensional from comparable features in several photos These points are joined to create a detailed point cloud depiction of the terrain and surface features through the technique of triangulation.

Next, the establishment of the dense point cloud, Agisoft Metashape, creates a comprehensive surface mesh.in order to create this mesh adjacent points in the point cloud are connected to create triangular facets, which produce a continuous surface representation that precisely depicts the topography of the study area. The surface mesh provides visual representation of the environment by combining data from the imaginary and the DEM to capture the subtle features of the surrounding topography and the road surface.

The final 3D model provides a comprehensive overview of the steady region, including all of its surface elements and geographical characteristics. Agisoft Metashape pro software guarantees that the model faithfully captures the morphology of the landscape and makes additional analysis and interpretation easier by integrating elevation data and photos. With the aid of this intricate 3D model, researchers can investigate the spatial linkages within the study area Spot important elements like potholes or elevation variations, and obtain insightful knowledge about the aspects of the environment.

7. Super-Resolution Application

The 3D model's resolution is increased by utilizing the sophisticated algorithms of Agisoft Metashape pro software. A higher-quality representation of the study region is produced by these methods, which also enhance texture clarity and mesh detail refinement (Inzerillo, L., Acuto, F., Di Mino, G.,2022). The program makes sure that small-scale elements, like potholes, are correctly recorded and reproduced in the final model by increasing resolution.

A. Improving Resolution

Improving the resolution of the 3D model created from the input photos is the main objective of the super resolution application. This entails Refining the model’s current features and interpolating more detail using algorithms.

B. Texture Clarity

The Super Resolution application concentrates on improving texture clarity in addition to resolution. This means that the 3D models' surface textures and patterns are rendered with greater fidelity, faithfully capturing subtleties and fine details.

C. Mesh Detail Refinement

The programme improves the 3D models. Mesh details in addition to its texture clarity. In order to get smoother surfaces and more accurate shapes, the mesh structure must be optimised to better match the geometry of the scene that was captured.

D. Small Scale Element Preservation

Maintaining small scale elements in the model is one of the main goals of the Super Resolution application. This contains characteristics that might be important for study under interpretation Such potholes cracks are other surface imperfections

E. Algorithmic Sophistication

To achieve super resolution Agisoft Metashape pro software uses sophisticated algorithms and computational methods. These algorithms are meant to minimise distortions or artifacts while analysing the given data intelligently and extrapolating more detail

8. Final Model Quality

Agisoft Metashape pro software seeks to generate a final 3D model with more accuracy and quality by using super resolution. These improved models make decision making and analysis easier by giving researchers and analysts a more accurate and detailed picture of the scanned environment.

Overall, the super resolution application in Agisoft Metashape pro software is a Critical component of the 3D modelling workflow, enabling the creation of high-fidelity models with the improved resolution texture, cleric and mesh detail.

9. Post-Processing

To further improve the 3D model's detail and clarity, other post-processing techniques may be used after super-resolution augmentation. Techniques for reducing undesired artifacts and sharpening the borders between features, such as edge enhancement, may be included in this. These improvements increase the model's appropriateness for further analysis and understanding as well as its visual quality.

To guarantee precise spatial alignment and scale, raw photos are georeferencing and orthorectified as part of the preparatory stage of the implementation procedure. From pre-processed pictures, Agisoft Metashape then creates a Digital Elevation Model (DEM), which provides precise elevation data necessary for detecting surface differences. After that, the program manipulates the photos to create a realistic 3D model of the research area, complete with accurate depictions of the road surface. Agisoft Metashape's super-resolution algorithms increase texture clarity and mesh details to boost the 3D model's resolution. Steps in post-processing, such edge enhancement and noise reduction, further hone the model to provide more detail and clarity.

10. Evaluation and Validation

To determine correctness, the finished 3D model is subjected to a thorough review process that makes use of measures such as Root Mean Square Error (RMSE) and compares it with ground truth data. As a quantitative indicator of the variation between expected and observed values, RMSE offers important insights regarding the functionality of the model. Reliable sources or manual measurements provide ground truth data that may be used as a benchmark to confirm the model's reconstruction's correctness.

3.3 Experimental Design and Procedures

3.3.1 Design of Monitoring Experiments and Parameters Choosing the Right Sample Size

Selecting the right sample size is crucial to guaranteeing the validity and applicability of the research results. The required level of confidence, research objectives, and statistical considerations all play a role in determining how many potholes need to be watched. Calculations based on variables including the estimated effect size, population variability, and desired degree of statistical power are part of statistical considerations. These computations aid in guaranteeing that the sample size is adequate to identify significant variations in the features of potholes and pavement state. The purpose of the study will ultimately determine how big and how focused the monitoring operations should be. If the objective is to evaluate the efficacy of a pavement maintenance program in mitigating the occurrence of potholes, for instance, a larger sample size could be necessary to capture changes across various treatment locations and circumstances. The intended degree of confidence expresses how certain the researcher is in the veracity of the study's conclusions. Larger sample sizes are usually needed for higher confidence levels in order to lower the margin of error and improve the dependability of the findings.

1. **Data Gathering Periods**

Determining the data collection frequency is essential for recording changes in pavement condition and pothole occurrence over time. Optimal data collection intervals guarantee that changes in pothole size, severity, and geographical distribution are carefully observed during the research period. Data collection periods are established depending on parameters such as the pace of pothole creation and degeneration, seasonal fluctuations in meteorological conditions, and the availability of resources for monitoring operations. For instance, more frequent data gathering could be required in areas with severe winter weather.

Furthermore, data collecting intervals could change based on the particular goals of the research. Data gathering may take place at regular intervals over a prolonged length of time for long-term monitoring programs that attempt to evaluate the influence of seasonal fluctuations or pavement repair efforts on pothole development.

2. Measurement Factors

It is essential to define measuring variables in order to precisely characterize potholes and evaluate the state of the pavement. To offer thorough insights on road surface degradation, parameters including pothole dimensions (e.g., length, breadth, depth), severity rating, and geographic distribution are carefully chosen. Measurements of potholes' length, breadth, and depth are used to describe their physical attributes and determine how serious they are. In order to prioritize repair and maintenance operations, pavement management authorities may use standardized scales or criteria for severity evaluations.

The organization and dispersion of potholes within the studied region are referred to as spatial distribution. Pothole patterns and hotspots may be found by mapping the geographical distribution of potholes, which helps direct resource allocation and focused remediation tactics. In general, the goals of the study, the unique features of the research field, and the resources available for data collecting and analysis serve as a guidance for choosing measurement variables. Researchers may guarantee the quality and dependability of their pothole detection and monitoring efforts by specifying precise and pertinent measurement variables.

3.3.2 Data Collection Protocols and Instrumentation

To guarantee that correct and trustworthy data are gathered for analysis, data collection techniques and instrumentation are crucial parts of monitoring investigations. Here’s a summary of the main points.

1. Unmanned Aerial Vehicles

A key methodological concern in the process of gathering data for aerial imaging and photograph metric analysis is the choice of UAV platforms.to guarantee peak performance and high-quality data, Researchers assess their number of factors.

A. Sensor Resolution

Aerial imaginary quality and details are directly impacted by the sensor resolution of UAV cameras. Researcher's priorities UAV platforms equipped with high resolution sensors to capture the details and subtle features of the research area. Methodologically, they analyse sensor specifications, such as pixel count and sensor size, to ensure appropriate image clarity and sharpness for accurate analysis.

B. Payload Capacity

The term payload capacity describes the UAV's capability to hold extra hardware such sensors cameras under navigation systems. In terms of methodology, researcher's asses UAV platforms, according to their ability to carry the equipment recruit for data gathering in their payload. These evaluation makes sure the chosen UAV can support the necessary hardware without sacrificing performance or flying stability.

C. Flight Endurance

when choosing a UAV, especially for extended or extensive data collecting missions, flight endurance is a crucial consideration in order to make sure the chosen UAV can continue to fly for the necessary amount of time, Researchers take into account Including battery life, flying range and endurance qualities in order to ensure continuous and uninterrupted functioning. They methodologically evaluate flight endurance to reduce their need for battery replacements and resourcing during data collecting.

2. Navigation and Positioning Systems

Methodologically researchers give performance to UAV platforms that have sophisticated navigation under positioning capabilities Such initial navigation systems (INS) and GPS. Exact flight control and aerial imaging georeferencing depend on these systems Exact location under orientation data. Spatial consistency and alignment in data obtained may be maintained by researchers by guaranteeing the dependability and precision of navigation systems.

3. Methods of Ground Truthing:

The use of ground Truthing techniques is essential for confirming and Vedic the correctness of data gathered from UAVs. To guarantee the accuracy of aerial images, Researchers employ a range of methodologies in manual inspection. The study region is physically inspected by researchers in order to verify features seen in aerial photography. This technique enables the direct validation of characteristics found in UAV photography, such as infrastructure assets, surface abnormalities and potholes. To quantify and validate ground features found in aerial images, instrumentation and measurements involve using calibrated instruments and measurements. Techniques to measure the size, distance and elevation of features like part tools or infrastructure components. For example, one can use digital Calipers, GPS receivers or laser range finders, by offering quantitative data for validation and comparison. These measurements improve their precision and dependability of information obtained from UAVs.

4. Instrumentation

By deploying sensors and other data-collection tools, UAV footage is enhanced with more information. This might involve the use of accelerometers to gauge the roughness of the pavement, infrared cameras to identify underlying flaws, and GPS devices for georeferencing. The particular goals of the research and the characteristics being measured determine which equipment is best. To guarantee the precision and dependability of the data gathered, equipment must be calibrated and maintained with care.

3.3.3 Statistical Analysis and Evaluation Criteria

This section outlines the statistical techniques and assessment criteria applied to the monitoring data analysis, which are essential for determining the precision and dependability of the produced outcomes. The following elements are necessary for this procedure to function:

1. **Metrics for Accuracy Assessment:**

Metrics for accuracy assessment are essential for assessing how well monitoring systems are doing. The Root Mean Square Error (RMSE), which calculates the average difference between values that are predicted and those that are observed, is one such statistic. When it comes to identifying disparities and areas that need development, Root Mean Square Error (RMSE) offers valuable insights into the correctness of Digital Elevation Models (DEMs) generated by photogrammetry.

2. **Regression Analysis**

This technique is used to identify correlations between the variables in the observational data. With the use of this statistical approach, trends and patterns may be found, leading to a more profound comprehension of the underlying causes of the occurrences that are being observed. The strength and direction of correlations may be quantified using regression analysis, which helps to drive later decision-making procedures.

3. **Testing Hypotheses**

Is an essential technique for deriving conclusions from observational data. Researchers can determine the importance of observed links or differences in the data by creating null and alternative hypotheses and doing statistical tests. The robustness of inferences made from monitoring experiments is increased when hypothesis testing is used to validate research findings and assess the statistical significance of experimental outcomes.

Chapter 4

Case studies

4.1 Overview of Selected Study Sites

4.1.1 Description of Study Locations and Geographical Features

To explore the effect of Detection of potholes in the road infrastructure using integrated UAV-based technology on Gustave Eiffel University, France is used in this case study. The précised geographic coordination of the study area is 48.8397° N latitude and 2.5867° E longitude. Concrete, asphalt and composite are the three types of pavements found in the university campus. Concrete pavements structure consists of typical concrete materials like cement and aggregate and often secondary cementitious materials are added to enhance the property of concrete. These pavements are subjected to long life with low maintenance, wear resistance, flexural stress, load carrying capacity, durability, rigidity and sustainability. So it can be used in all types of pavement application. Some of the common distress patterns are cracking, spalling, and faulting, etc. Asphalt pavement is material consisting of 90-95% of aggregate and 5-10% of bitumen and subjected to strong adaptability, flexibility, smoothness, heat resistance, etc. Distress in asphalt pavements are rutting, pothole, fatty surface, edge crack, settlements and upheaval, etc. Composite pavements structures comprise two or more layers that combine different characteristics and act as a composite material. France is one of the European countries, extensively using composite pavement which accounts for about 30% - 50% of their main road network. Typically these pavements consist of flexible hot mix asphalt (HMA) layers as a wearing surface course over a concrete layer. This semi-rigid pavement structure is subjected to its long life with good surface characteristics, structural capacity and rapid renewal if it is essential. Depending on the composition of the material the characteristics and distress pattern may differ. Composite pavement structure may develop different types of defects which are very similar to the flexible pavements due to the exposure of asphalt concrete layer and some of the major defects are cracking, distortion and disintegration.

Environmental variation may significantly affect the pavement materials and it leads to minimizing the performance and structural health of the pavement. Some of the major parameters are temperature, humidity, precipitation, sunlight exposure, etc. France is vulnerable to the impacts of climate change from increase in temperature, more intense rainfall with uncertain change in the frequency, heavy snowfall and severity of storms. The observed temperature for the study area ranges from -2°C (winter) to 35°C (summer), 60-80% of average humidity, 650mm of average rainfall and 2000 hours/year of average sunlight.

4.1.2 Road Infrastructure Characteristics and Pothole Distribution

Concrete pavements are designed based on a structural cement concrete slab with sufficient strength to resist the load from traffic and the loads are equally distributed to the sub-grade of the soil. The life expectancy of concrete pavement is typically for about 20-30 years or more depending on the factors like quality of concrete, subgrade condition, weather condition, thickness of the road and type of traffic that the road carries. Due to its various advantages the concrete pavements stand best in the perspective of maintenance and manageability with low cost. It has the benefits of reducing environmental impact, provides high road reflection rate which helps to reduce the surface heat and because of its hardness characteristics it improves the fuel efficiency especially for large vehicles. It has a tendency to contract in dry condition and expands in wet condition due to temperature changes. Concrete pavement is provided if the daily traffic is more than 2000 tons/day. Potholes are the most common distress in the concrete pavement with the minimum dimensions of 150mm.

Asphalt pavements are designed based on load distributing characteristics of the layered system and the loads are not uniformly distributed to the sub-grade. Generally the life span of these pavements can last between 15-20 years with great maintenance. Managing its structural integrity and functional properties at a satisfactory level within its nominal design-life when exposed to the effects of the environment and the expected traffic loading. Asphalt pavements are most effective for the traffic volumes of 150 to 600 vpd and also for more than 600 ranges, which means low to medium road traffic conditions. Maximum daily traffic capacity of bituminous pavement is 1500 tonnes per day. Vehicles that weigh more than the pavement was intended to bear can damage asphalt pavement. Damages can occur whether the vehicles are driving on the pavement or parked on it. Exceeded traffic volume of the pavement may cause small crack formation and lead to potholes on the surface of the road. Composite pavement is a cost-effective pavement alternative for high volume roadways. This multi-layered structure provides a smooth, safe and quiet driving surface with a stiff and strong base. These kinds of pavement are widely used in heavy traffic volume and long life pavement with minimum rehabilitation. The expected life spans of the composite pavement are designed to be 40 years. The most common distress on the composite pavement is reflection cracking. It occurs when the crack obtained on the surface of HMA is transferred from movement at the joint or crack in the underlying concrete base. Some of the factors like types of pavement, durability, traffic volume, traffic flow, load bearing capacity, weather condition and the distress are formed on the surface of pavement. Due to improper maintenance small defects lead to severe damage. Average potholes depth is around 60 mm–100 mm and for a more severe case it is bigger than 100 mm.

4.2 UAV Image-Based Monitoring Process

4.2.1 Planning and Execution of Drone Flights

Water-filled potholes on the pavements for the study area are captured using UAV aerial photography. Drone flight plan is the combination of instructions like coordinate, speed, altitude, heading, direction and more which serves the purpose of guiding the drone to achieve the mission. Aircraft are scheduled to ensure coverage area and the precise height of 3.36 meters required to be flown with 1.08 mm/pixel of possible ground resolution. Flight path planning is created using the flight planning software. The software was selected based on consideration of compatibility, collaborative environment, cross device and cross plan functionality, offline access and KML support. Generally, there are two types of drone flight paths that can be plotted: grid path and waypoint path. For this research, a grid pattern is used for plotting the flight route. It is the best method used for mapping missions designed to collect image for processing into 2D and 3D data. For 3D data, it is required to consider a 'cross-hatch' pattern, a gimbal angle of 70-80 degrees and even adding an orbit pattern around the grid flight. With the ideal flight planning software, the mission is created and scheduled, manage the mission with a calendar, assign pilots and equipment, send notification, check airspace and weather conditions and execute the flight plan.

Safety should be the first consideration to ensure secured drone operation. It is important to inspect thoroughly before the operation of a drone by ensuring all navigation systems, sensors and all other components are functioning properly. Wind speed, weather condition, collision with other aircrafts, technical failures, obstacles like buildings or power lines that can interfere with drone flight path, electromagnetic sources which can disturb the signal controlling, ensuring drone software accessibility to local rules and advisories for the study area etc., are taken into account to evaluate the potential risk for the operation. Mitigate risk by establishing strategic risk assessment and contingency plan in place. So that it can minimize the livelihood of accidents and property damage (Inzerillo, L., Acuto, F., Pisciotta, A., Dunn, I., Mantalovas, K., Zeeshan, M.,2023). By taking the measures and safety considerations, planning and execution of drone flight can ensure the secure and responsible use of unmanned aerial vehicles (UAVs) in an image acquisition technique.

4.2.2 Image Acquisition Techniques and Equipment

Image of pothole on the pavement is captured using dji matrice 300 RTK drone equipped with high quality sensor camera of model ZH20. DJI matrice 300 RTK is an advanced drone inspired from modern aviation systems. It enables transmission range up to 15 Km and offers 55 minutes of maximum flight time, 23m/s speed and 12m/s wind resistance and it can be configured with multiple payloads up to the maximum capacity of 2.7Kg. This UAV flight is provided with a self heating battery, anti-collision beacon, Sensing and Positioning system for 6 Direction which helps to keep the aircraft and the mission safe. Both the drone and camera can operate in the temperature ranges from -20° to 50° C. The equipped camera ZH20 with the sensor of 1/2.3" CMOS, 12 MP is provided with diagonal field of camera (DFOV) angle for about 82.9°C with 4.5mm focal length. And the camera is configured to capture the images with the resolution of 4056 x 3040 pixels in JPEG format. For a high quality image capturing, the camera is calibrated to auto exposure mode (to prevent lighting problems) with the shutter speed of 1 - 1/8000, aperture f/2.8.

Totally 48 images of potholes on the pavement of the study area, were captured from 48 camera stations by the sensor camera attached with the aircraft matrice drone at a flying altitude of 5m and 1.08mm/pixel ground resolution. Each flight covers an area of about 118m^2 and pixel size of 1.6 x1.6 μm. Each picture provided with the sufficient overlapping of 80% for both front and side are maintained between the consecutive photographs taken for the entire flight path. All the collected data are recorded which helps to improve the accuracy of 3D model generation from the software.

4.2.3 Quality Control Measures and Data Validation

The collected aerial photographs are preprocessed with geo-referencing, orthorectification and radiometric correction process for the accurate coordination with real world geographic position of the study area. The preprocessed images are used in the “Agisoft Metashape pro software” for the generation of digital elevation model (DEM) and high resolution 3D reconstructed model for the study area can be created with the application of super resolution algorithm. And the post-processing techniques are used to enhance the quality of the model for better understanding. The evaluation and validation procedure are implemented to ensure the accuracy and reliability of the refined data using ground truthing method and image validation techniques. Ground truthing method is used for verifying the accuracy of collected data. It is the process in which a feature on an image is compared to the ground reality in order to verify the image features. The physical attributes of the pothole on the pavement are measured from the multi-processed image using the ruler tool or manual measurement data provides to confirm the 3D reconstructed model accuracy. Root mean square error (RMSE) method is used to analyse the dimension of the pothole from the image. RMSE or root mean square deviation (RMSD) is a standard deviation of the residuals and it is compatible with some of the more common statistical assumptions. Either one of two closely related and frequently used measures of the differences between true or predicted values. It presents the difference between the predictions that fall from measured true values using Euclidean distance. This method is commonly used in prediction and regression analysis to verify the experimental results and RMSE inputs have a direct relationship with the correlation coefficient. Based on the thumb rule, the RMSE value lies between 0.2 to 0.5 it shows that the model can relatively predict the data accurately. If the value is adjusted more than 0.75 then the model accuracy rate will be good. Low value shows the model is more accurate in prediction. By comparing ground truthing method with root mean square error (RMSE) technique the accuracy of the data can be determined.

4.3 Results of Pothole Detection and Analysis

4.3.1 Accuracy Assessment Metrics and Criteria

The performance of pothole detection algorithms are evaluated using the Statistical method of regression analysis. The main purposes of the regression analysis is to estimates the relation between true value & predicted value with the assessment of model performance by means of measuring the similarity among the two sets, and to evaluate the quantitative measures of the model by providing each several metrics with its own strengths and limits to assess the model suitable for the statistics. Few assumptions are required to be taken into consideration while analyzing the regression model. They are: (1) relationship between the variables must be linear, (2) variance of the variables and error term remains constant, (3) All explanatory variables are independent from one another, (4) all variables are normally distributed. Some of the common evaluation metrics for regression analysis are Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), R-squared (Coefficient of Determination), and Mean Absolute Percentage Error (MAPE). By using these regression specific metrics, accurate and effective predictions for the model are evaluated. Linear Regression, Decision Trees, Random Forests, and Support Vector Machines (SVM) are the machine learning algorithms for prediction, based on a regression concept which is used in practice.

Accuracy is a metric which measures how often the machine learning models can correctly predict the results. The overall accuracy for all the regression based models of machine learning algorithms ranges from 86.05% to 97.81%. Generally, an accuracy rate greater than 70% is considered as a great performance model. If the accuracy of the model ranges from 80% to 90% is not only ideal but also realistic and consistent for the commercial standard. But 100% accuracy is not acceptable in this case; it is due to over-fitting. It occurs when the model tries to cover all the data points or more than the required data points present in the given dataset. Accuracy is a good metric when the model classes are balanced but it's not reliable while dealing with imbalanced problems. Other metrics are needed to be analyzed for the model before concluding the model performances. False positive is metrics used to measure the performance of the model. It is the outcome from the model that incorrectly predicts the positive class. Similarly there is a case of false negative, when the model incorrectly predicts the negative class. Precision-recall is another metric used to measure the success rate of prediction when the classes are very imbalanced. Precision indicates out of all positive predictions (actually positive) while Recall indicates out of all actually positive values (predicted positive). Precision-Recall curves summarize the trade-off between the true positive rate and the positive predictive value for a model using different probability thresholds. A high area under the curve shows high recall relates to a low false positive rate and high precision relates to low false negative rate. Systems with high recall with low precision rate or low recall with high precision rate are labeled as incorrect while high precision and high recall with all the results are labeled as correct. For the accuracy assessment, all the metrics evaluate the quality of regression models and help to make decisions from the overall performance evaluation.

4.3.2 Spatial and Temporal Distribution Analysis of Potholes

Potholes may start to develop from small cracks on the surface of the road due to repeated load and different environmental conditions which leads to the forming depression with a rough vertical side. Potholes can occur in all types of pavement but are a problem particularly associated with asphalt surfacing. Potholes form most frequently in the spring season. Freezing and thawing cycle accelerates the development of potholes. In winter, the temperature fluctuates from low to high that makes the pavement contract and expand. Water seeps into the road surface through the crack, collected under the subgrade and it leads to weakening or softening of the road foundation. It makes the road, which can no longer take the heavy weight of the vehicle. Most of the winter potholes are due to the cracks which allow the water to seep into the foundation. Once the water or moisture trapped under the surface of the pavement it freezes when the temperature drops and it may cause the pavement surface to expand and uplift. As the temperature rises the frozen ice melts and creates a hollow space between the pavement and sub-base. These temperature fluctuations can already weaken the pavement and the weight of the vehicle while driving over the weak spot the pavement gets collapsed and forms the pothole. Due to continuous traffic flow over the defected position the size of the pothole may expand. Each seasonal variation cycle creates more damage to the potholes by widening and deepening them. Potholes require the passage of vehicles to initiate and develop, so the distress most likely to occur below the outer wheel path closer to the road edge which is considered a vulnerable part of for the formation of the road. Potholes on both carriageway and footway are formed by shape edged depressions anywhere on the surface where all the layers of the roads are removed but the only difference between them is variation in dimension. For a carriage way horizontal dimension is identified as 250mm or more whereas for footway the maximum horizontal dimension is identified as 75mm. The holes on the pavement surface must be at least 40mm deep, and then only it claims as a pothole. Generally, the size of the pothole ranges from minimum 20mm deep with wider than diameter than 75mm to maximum 100mm deep with 300mm wider in any horizontal direction.

4.3.3 Interpretation and Discussion of Findings

This study provides detailed information about the formation and detection of potholes on the surface of the pavement. Investigated all environmental and physical factors including temperature variations, seasonal changes, traffic flow, traffic volume which influenced the formation and development of potholes. From traditional methods to advanced technology various pavement distress detection techniques are analyzed. Particularly for this research UAV-based technology is used due to its accuracy, efficiency and cost effectiveness. While implementing the unmanned aerial vehicle UAV- based pothole detection system, significant challenges are faced. Such as energy constraint, coordination between drone and ground control service, adverse weather conditions, flight path planning, flight endurance, onboard computational capabilities, obstacle detection and avoidance, performance analysis, security and privacy issue, air policing, etc.

Road maintenance is essential in order to preserve the road in a good condition, protecting the adjacent resources, user safety and providing efficient smooth travel. Improper maintenance results in rapid deterioration and failure of the road due to the major impact of adverse weather conditions and vehicle usage. While implementing road maintenance strategies following considerations are taken into account: (1) Improvement in safety, strength of carriageway and accessibility, (2) Economically efficient, (3) Ensuring environmental sustainability, (4) Promoting integration, (5) Develop long term road management plan, (7) Risk assessment, (6) Addressing the need of stakeholders.

Chapter 5

Results And Discussions

5.1 Analysis of Pothole Detection Results

5.1.1 Comparison of UAV-Based Detection with Traditional Methods

The traditional methods are the most commonly and widely used in practice for the detection of pothole and other pavements defects in road infrastructure. Visual inspection training, ground based sensor and survey, remote sensing technologies are the conventional methods used. Visual inspection is a manual method for detecting pavement distress with the naked eye which involves capturing the image with an inspection vehicle. It requires skilled professionals, it consumes more time depending on lighting condition and human factors, increases safety risk, and causes damage to the vehicles. And it required separate budget allocation for monitoring and maintaining purpose.

Ground sensor and survey method is comparatively advanced technology. Sensors play an important role in finding defects in the road. Using sensor, camera, spectral and laser scanners, synthetic aperture radar (SAR) it can collect a geospatial date. Some innovative sensor based models are proposed for monitoring and to check the durability of road conditions. This method may enhance the factors like rapidness, cost efficiency, sensitivity, working in a stable condition and low noise signal. However it is noted that these methods are not suitable for all cases with its time rigidity.

Remote sensing technology, for monitoring road satellite imagery and LiDAR (Light Detection and Ranging) techniques were used from aerial and space-based platforms. An integrated sensor system identifies the defects through automation and determines the exact problem in an efficient way. For detection and segmentation of a building, it is difficult to differentiate features between building and non-building class due to its pixel variation. This may lead to less accuracy and effectiveness in identifying the building from an aerial image. LiDAR is a valuable tool for monitoring road conditions and with its accuracy it can identify human activities, speed and direction. Instead of transportation applications, data is collected from the captured road features of Mobile Laser Scanning (MLS) systems and transferred via some other platforms. LiDAR boosts high-resolution, wide range of 3D data collection, even in difficult weather conditions. The LiDAR system is costly and efficiency is limited in extreme weather conditions due to its interference light beam path.

Unmanned Aerial Vehicles (UAVs) is an advanced technology which can give access to higher resolution aerial images by providing redefined texture, structure and spectral information of the building. UAV can be equipped with cameras, sensors, GPS to capture high definition images from various infrastructural elements for planning, execution, proper resource maintenance and ensuring the project schedule. Many types of UAV's are available but multi-rotor is commonly prevalent because of its controlled mechanism and high precision in positioning when compared with other types. It provides real-time data without any other expensive resources or equipment. Using drone methods along with aerial imagery and photogrammetric techniques, potholes can be detected with its geo-tagging capability and précised data information. The acquired image can be used for the vulnerability analysing process. Due to its lightweight, cost effectiveness and multi-sensory system it captures the data from various environmental factors like humidity, precipitation, sunlight and in different temperature conditions. It helps to create a large set of databases based on pothole pattern detection for the pavement maintenance activity. Data transmission is possible through long-range wireless communication facilitated with seamless connectivity between drones and ground stations. In an UAV method for pothole detection, various types of deep learning algorithms can be integrated for a higher accuracy of the image. Drones cover over a large area for data capturing and live road footage with straightforward image processing techniques can be approached. The accuracy of the model can be checked by geo-referencing technique with ground control points of the drone captured data.

The conventional methods are moderate, consume more time, costly, require bountiful resources, expensive tools and it involves human work which induces inaccuracy. The accuracy of the captured image is less because of its complexities in pixel variation that makes it difficult to identify the pothole defects. Unlike visual inspection and sensor methods, LiDAR technique does not measure objects for data collection as it is equipped in a vehicle with GNSS as a receiver and inertial measurement units (IMUs) to provide precise sensor status information. But LiDAR is costlier and its effectiveness is limited to certain conditions. By contrast, UAV- based methods are rapid, high flexibility, transparent, cost effective, data gathering with geo-spatial details, efficient to survey in an immense area in a timely manner, efficient in all environmental conditions and various kinds of regions. For enhancing the accuracy of the image sophisticated algorithms are integrated which is cost effective for the detection of defects in the roads.

5.1.2 Effectiveness of Super-Resolution Algorithms

Super resolution is an image processing technique, in the process of generating a high resolution image from the sequence of low resolution images. To improve the clarity and resolution of the aerial photography, the following factors are taken into consideration for an algorithms selection: Photogrammetric proficiency, Handling Big data sets, detailed reconstructions, Geometric accuracy, User friendly interface and Versatility and integration. Depending on the consideration advanced super-resolution are applied on Agisoft Metashape pro software by using DEM technique.

Agisoft Metashape pro is standalone software that performs photogrammetric processing of digital images and generates 3D spatial data to be used in GIS applications, documentation, visual effects production and indirect measurements of objects of various scales. It allows fast processing and provides high accurate result for both aerial and close-range photography with its accuracy upto 3cm for aerial and <1mm for close-range accuracy. Based on the distributed processing functionality it is capable of processing 50 000+ photos across a local cluster and also it is easy in cloud processing.

To improve the quality of the generated 3D model some parameters are required to optimize in Agisoft Metashape pro software setting. The parameters are overlapping, camera calibration, tie point position, dense cloud, optimization of resolution and interpolation. Recommended overlapping percentage for aerial projects should be 80% forwards and 60% sideward but typically it should be 80% if the value goes below than this it may affect the accuracy of the image alignment and dense point cloud production. For tie point position is the point limit, the amount of key points that should be tied together from each image. So by providing a tie point limit value, then the key points need to match it with another photo for them to be aligned. Key point limit, are the points Agisoft Metashape pro software should look for in each image. One point is one unique feature in an image. Recommended values for Key point limit: 20.000 - 60.000 Tie point limit: up to 40.000. Before creating the dense cloud clean model step needs to be done by the following value: Reprojection error should be below 0.4, Reconstruction uncertainty should be at 200, Projection accuracy value is 2. For Dense cloud Quality goes from Ultra high to Lowest. For Ultra High processes original photos recommended value for High downscales by a factor of 4, Medium downscales by 16 Low by 64, Lowest by 256. Depth filtering is a function that sorts out outliers in the model which Goes from disable to aggressive, Mild is less strict filtering of features and Aggressive is more struct in terms of filtering out features.

In a pre-processing stage, raw photos captured from UAV are processed with geo-referencing and orthorectification procedures for real spatial connections and dimensions of the study area. Geo-referencing is a process of relating aerial images to ground systems of geographic co-ordinates. Adding geo-graphical information to the image the software can spot the image in its real world location. The relevant coordinate transforms are typically stored within the image file though there are many possible mechanisms for implementing this process. Geo-referencing in the digital file allows basic map analysis to be done, by pointing and clicking on the map it determines the coordinates of a point, calculates distances and areas, and to determine other spatial information. Orthorectification is the process of removing distortion to assign more accurate coordinates to the image. Every pixel in the image is depicted by removing the effects of hills, valleys on the data to create a plain metric image at every location with consistent scale across all parts of the image. Once data has been ortho-rectified, it may be easier to compute distances, areas and directions more accurately from the image.

After pre-processing, a DEM model is generated for the processed image. DEM is a raster representation of continuous surface referencing the surface of the earth by excluding artificial structure, vegetation or any other surface object. Detecting minute surface irregularities like potholes can be done by enhancing the resolution and its precision in the DEM model. Integrating LiDAR data and stereopair matching techniques in the DEM procedure based on advanced algorithms, it can provide accurate specific elevation information for the model. LiDAR is based on sensor technology; it can provide highly accurate 3 Dimensional measurements. Data is collected from UAV using sensors which detect the reflections of a pulsed laser beam. The reflections are recorded as millions of individual points known as “point clouds” which reflect everything from the surface including structures and vegetation. The stereopair matching is a process of matching two or more images of the study area from slightly different viewpoints which gives stereoscopic effect. The difference between the images is called parallax. Stereo-pairing can be obtained from aerial photographs, digital images and sensor data. Based on the principle of OrthoEngine which uses correlation image to extract matching pixels from two or more images and then uses the sensor geometry from the computed math model to calculate x, y, and z positions. Agisoft Metashape pro software supports stereoscopic mode with the help of Quad Buffered Stereo technology. Metashape supports simply anaglyph display mode (for red/blue glasses) as well as hardware stereo mode that assume polarization glasses and professional grade hardware (GPU that supports quad-buffer stereo and 3D monitor). From the DEM data positional and elevation errors can be quantified by error modelling and uncertainty quantification techniques. For the creation of a comprehensive image of the landscape can be obtained by geostatistical interpolation DEM fusion technique. Geostatistical interpolation techniques use the statistical properties of the measured points and it quantifies the spatial autocorrelation among them and accounts for the spatial configuration of the sample points around the prediction location. Geostatistical Analyses can provide global polynomials as a global interpolator and inverse distance weighted, local polynomial, radial basis functions, kernel smoothing, and diffusion kernel as local interpolators. With these advanced techniques digital elevation model DEM is created for the aerial image of potholes in roads.

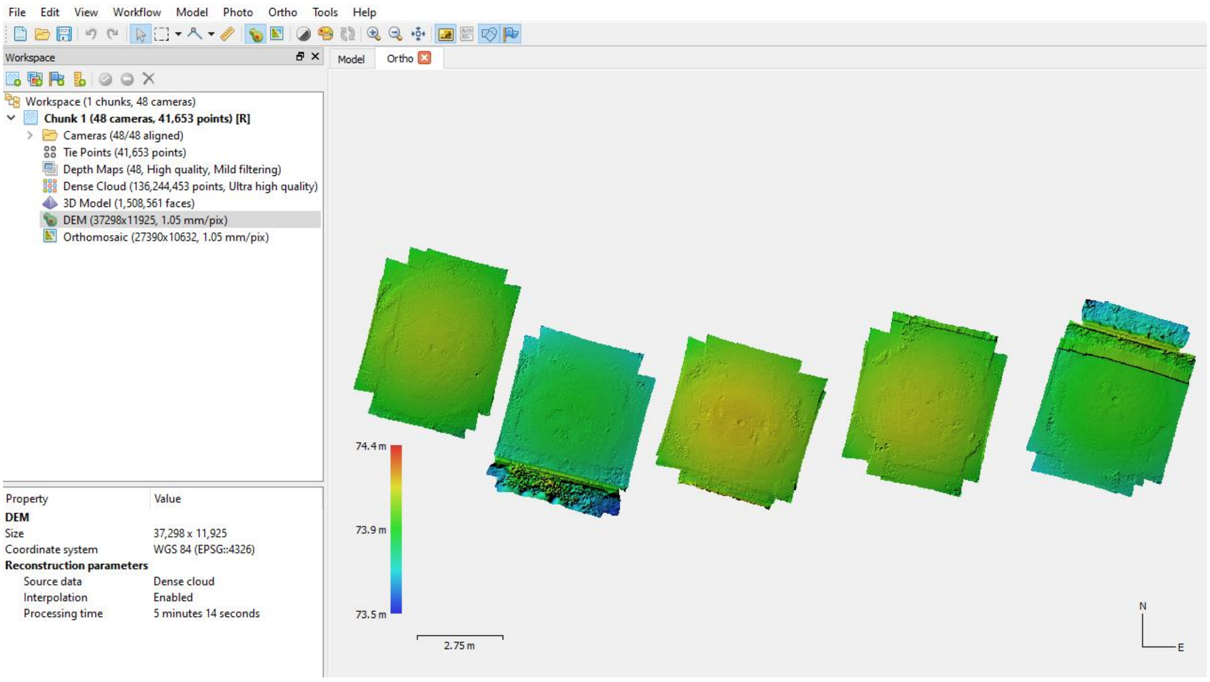


Figure 3: Digital Elevation Model

High resolution 3D model for the project study area is created by dense point cloud technique. Dense point cloud generation is based on depth maps calculated using dense stereo matching. Depth maps are calculated for the overlapping image pairs considering their relative exterior and interior orientation parameters with some adjustment. Multiple pairwise depth maps generated for each image are merged together into a combined depth map, using excessive information in the overlapping regions to filter wrong depth measurements. Combined depth maps generated for each image are transformed into the partial dense point clouds, which are then merged into a final dense point cloud with additional noise filtering process applied in the overlapping regions. The normals in the partial dense point clouds are calculated using plane fitting to the pixel neighborhood in the combined depth maps, and the colors are sampled from the images.

For every point in the final dense point cloud the number of contributing combined depth maps is recorded and stored as a confidence value. After the creation of dense point clouds for every single point, the triangulation techniques are applied to join the points for the creation of detailed point cloud depiction of the terrain and surface features.

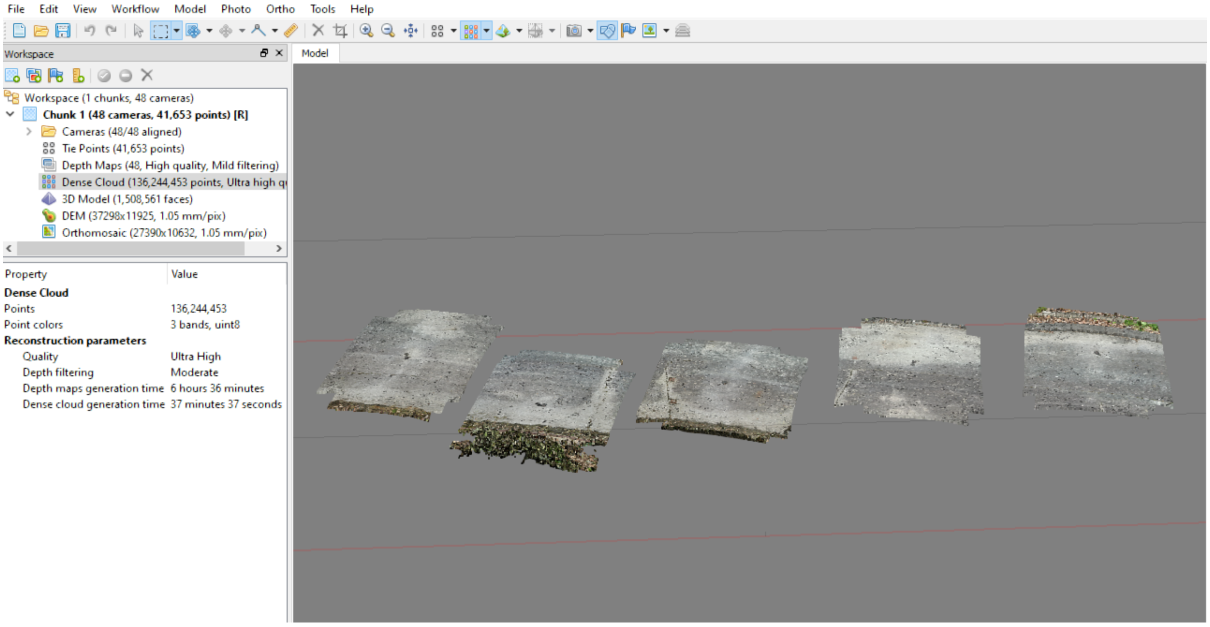


Figure 4: Dense Point Cloud

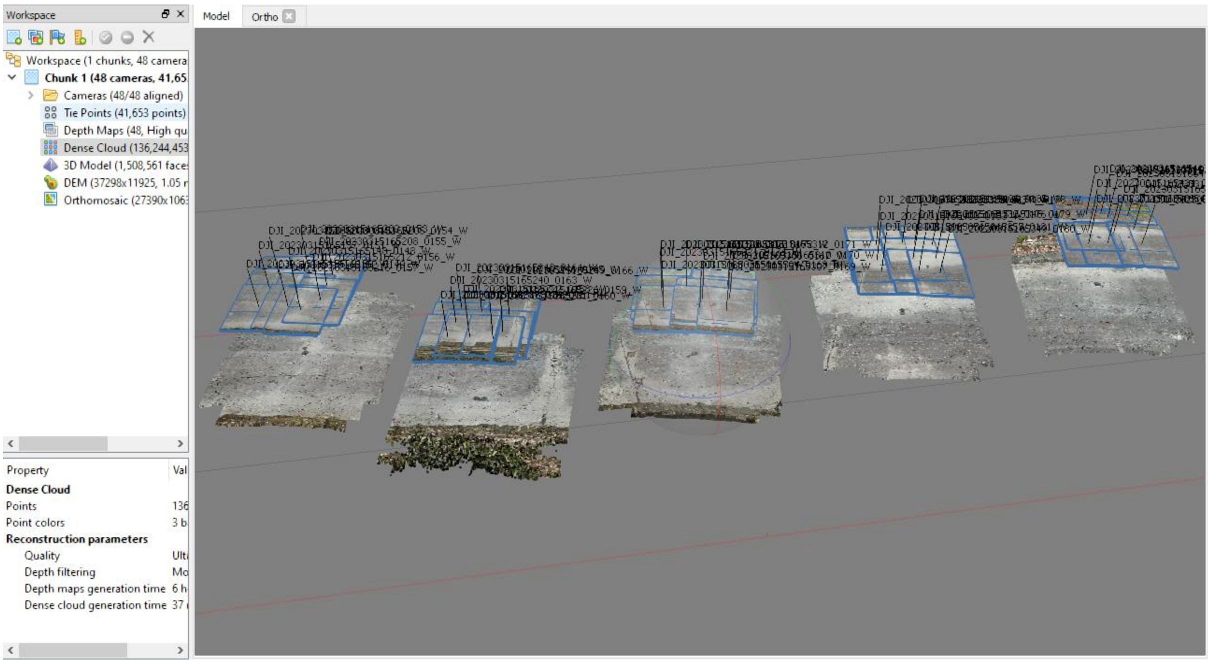


Figure 5: Detailed Dense Point Cloud

With the help of the software, by combining the data from the image and DEM the features are captured and the surface mesh is created by triangular facets technique. Surface mesh can provide visual representation of the study area with precise information.

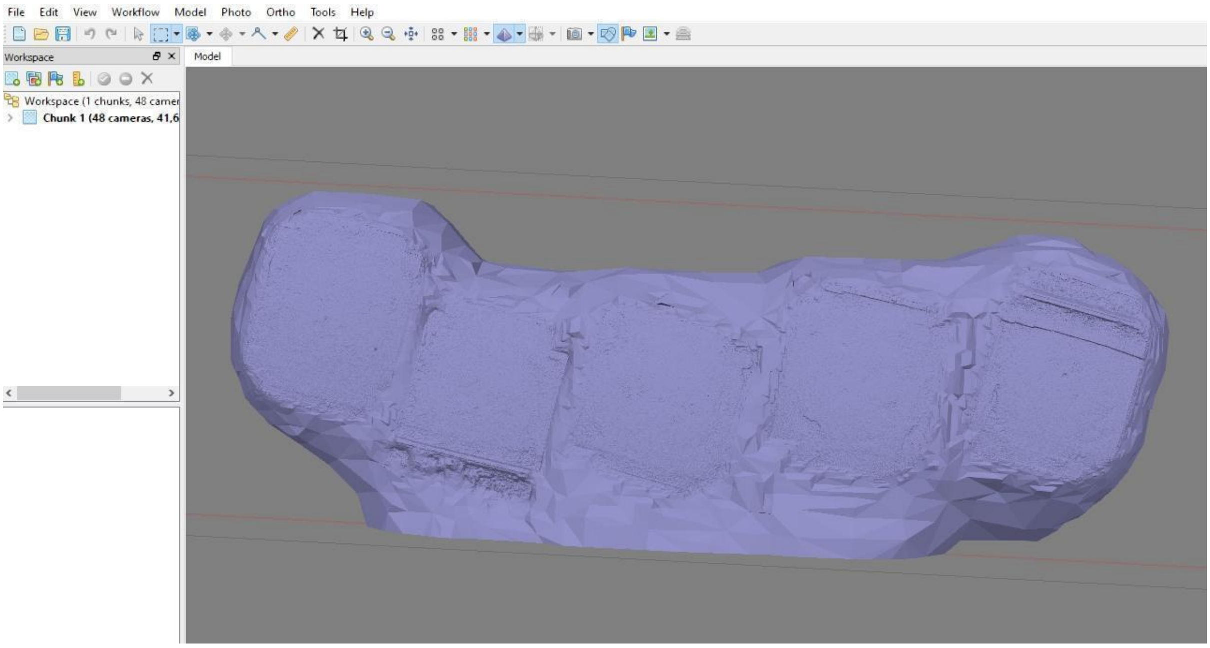


Figure 6: Created Surface Mesh For The Study Area

With this complex procedure, a high resolution 3D reconstructed model is created by utilizing data from pre-processed images and the resulting DEM model.

For increasing the overall quality of the existing 3D reconstructed model, it is achieved by the application of super-resolution algorithms in Agisoft Metashape pro software. Only by increasing the resolution and reproducing in the final model, minute elements like potholes can be detected from the data. The main concept of super resolution algorithms is to generate a high resolution image from a low resolution image. High resolution images offer high pixel density, so it can provide more details when compared with the original or any processed image. Super resolution in the image is done by improving resolution for the refinement of the models features; texture quality for rendering the patterns with fine details; mesh detail refinement for to a better geometry, smoother shape and smooth surface on an image; small scale element preservation for maintaining a minute features on the model; Algorithmic sophistication for the minimization of distortions while analysing the data. Final 3D model is generated with greater accuracy and high resolution quality. Post processing techniques are required to improve the clarity and details in the 3D model. It includes edge enhancement, noise reduction for sharpening the features and satisfying the artifacts which helps to improve the model for understanding and analysis.

Evaluation and validation of the 3D model is obtained by reviewing the process and comparing it with ground truth data to determine its correctness. For quantification and validation, ground truthing technique is applied for confirming the correctness of data gathered from dji matrice 300 rtk drone. This technique is a performance of surface observations and measurements of the features on ground surface that are being studied on the remotely sensed digital image or by manual inspection. Using dji matrice 300 rtk drone photography, potholes in the pavements are directly validated with a ruler tool from software to measure the size.

Figure 7: Measurement of Pothole using Ruler Tool.

For a Statistical analysis and evaluation Criteria Root Mean Square Error (RMSE) method is applied. RMSE is a most commonly used method for evaluating the quality of prediction. It is one of the main indicators for a regression model. It measures the average difference between predicted values by a model and the actual values and it provides an estimated accurate value.Root mean square error can be expressed as,

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \|y(i) - y'(i)\|^2}{N}}$$

where N is the number of data points, y(i) is the i-th measurement, and y'(i) is its corresponding prediction.

5.2 Evaluation of Weather Impact on Pothole Detection

5.2.1 Influence of Seasonal Weather Variations

Potholes on the road can be formed by the physical weathering like seasonal changes and temperature variations due to it heating up and cooling down of moisture inside the pavement, combined with pressure from different directions. Three main elements contributed to pothole formation are surface cracks, water, and traffic. Seasonal variations form one of the basic components of the time series. They are variations of a periodic nature that recur regularly. Weather can be highly variable on a daily, weekly, or even yearly basis. One day it might be sunny and the next it might be cool. Climate**,** on the other hand, doesn't change day-to-day due to its longer time scales and averages. However, climate is variable as well**.** Climate variability is the way aspects of climate such as temperature and precipitation which differ from an average. Climate variability occurs due to natural and sometimes periodic changes in the circulation of the air and ocean, volcanic eruptions, and other factors. The main causes for temperature, humidity, precipitation and sunlight exposure are climatic variation. Precipitation is water released from clouds in the form of rain, freezing rain, sleet, snow, or hail. Precipitation is the main way atmospheric water returns to the surface of the Earth. Most precipitation falls as rain. And humidity is usually called relative humidity. It is the amount of water vapour actually present in the air, expressed in percentage of the maximum amount of water vapour the air can hold at the same temperature. This weather cycle influences a greater negative impact on pavement distress. Freeze–thaw cycles and water ingress are two of the most frequently quoted contributing factors. In the Freeze-thaw cycle the temperature will fluctuate, as the moisture that seeps into cracks on the road can freeze during cold spells. As water freezes, it expands, applying pressure on the surrounding road and widening existing gaps. Due to contraction and expansion potholes can be formed on the pavement by water entering into the pavement it may have a chance to freeze, then the water occupies some space under the pavement then it will expand, bend, and crack. When the ice melts, the pavement contracts which form voids in the surface under the pavement, where water can get in and be trapped. If the water freezes and thaws over and over, the pavement will weaken and continue cracking. In the summer season, extensive exposure to the harmful UV rays from the sun can cause surface oxidation, fading and structural integrity loss which gives way to surface degradation and rapid disintegration on the pavement. In the rainy season Abundance of rainwater can slowly erode the surface of the road and the internal structure gets disturbed. This opens up a void within the aggregate for more water to pool and debris to settle. As the water continues to wear down on the road more cracks and potholes will form over time.

Detection of potholes on the road in adverse weather conditions like haze and snowfall will affect the convincingness of the high quality image captured from the detection system. And in a high temperature condition identifying, endorsing and governing the pothole detection system will be strenuous. Night vision and inferior lighting accuracy of pothole detection systems installed in autonomous vehicles may be significantly impaired.

5.2.2 Strategies for Weather-Aware Pothole Detection

For weather-aware pothole detection it is essential to adopt an integrated technology for automation. Hybrid technology for this study is obtained by combining the techniques used for both forecasting weather and pothole detection which includes image processing techniques and Machine Learning (ML) models trained on weather data. Forecasting weather is an application of scientific techniques and technology for the prediction of atmospheric conditions at a certain location and time (Siddharth Singh et al., 2019). With the advancement in technology, machine learning is used for its greater accuracy and efficient prediction. Machine learning is a branch of Artificial Intelligence technology which focuses on processing the input data with the help of algorithms. It estimates a pattern for the data and using the error function prediction is evaluated and the model is optimized. The selected algorithm repeats this iterative process from "evaluate to optimize", updating weights autonomously until a threshold of accuracy has been met. Machine Learning uses statistical models for pattern identification and relationships in historical data and uses that information for prediction. Weather-aware ML models consider a wide range of metrics such as temperature, humidity, wind speed, cloud cover, data from satellites, radar and weather stations. Several machine learning techniques are available for weather forecasting and pothole detection and some of them are artificial neural network (ANN), time series based recurrent neural network (RNN), support vector machine (SVM), multiple linear regression, decision tree, Convolutional Neural Network (CNN), random forest, extreme gradient boosting and multilayer perceptron, etc., for weather-aware ML. Naive Bayes, K-means clustering, Convolutional Neural Network (CNN), you only look once (YOLO), fuzzy C-means clustering, support vector machine (SVM) etc., for pothole detection based ML.

Image processing technique is the process of converting an image from raw photos into a digital form and performing certain operations to obtain detailed information from the image. The image processing technique usually treats all images as 2D signals while applying certain predetermined signal processing methods. The main functions of this technique are noise reduction and increase the contrast of planetary details, segmentation, image resizing, colour correction and features extraction. Fundamental step for image processing techniques are: Image acquisition is an initial step as a pre-processing of an image it involves retrieving the data from a source, enhancing the image by highlighting the features depends on the need, appearance of the image are improved by Restoration using mathematical or probabilistic models, image colour processing, wavelets processing for various degree of resolutions, compression for storage purpose, Morphological Processing, segmentation, for regional properties and qualitative information extraction representation & description process are required, labelling an object by recognition step. Enormous types of image processing algorithms are applicable based on ML and some of them are convolutional neural network (CNN), Canny edge detection technique, Contour detecting technique, Hough transform technique etc.,

All machine learning techniques for pothole detection, weather prediction and image processing have their own functionality and specification. Strategy for weather-aware pothole detection and image processing technique of a model is recommended by few of the selected methods based on its familiarity among the three processes. And they are SVM, CNN, Canny edge detection techniques.

1. **Support Vector Machine (SVM)**

It is a most powerful and commonly used machine learning algorithm which uses supervised learning models to solve complex classification, regression, and outlier detection problems by performing optimal data transformations that determine boundaries between data points based on predefined classes, outputs. The main aim of the SVM algorithm is to create the best decision boundary which can segregate n-dimensional space into classes so that it can place new data points in the correct category in the future. This best decision boundary is called a hyper-plane. For the creation of hyper-planes extreme points or vectors are used. These extreme cases are called support vectors, so this algorithm is termed as Support Vector Machine. Consider the below diagram in the two different categories that are classified using a decision boundary or hyper-plane.

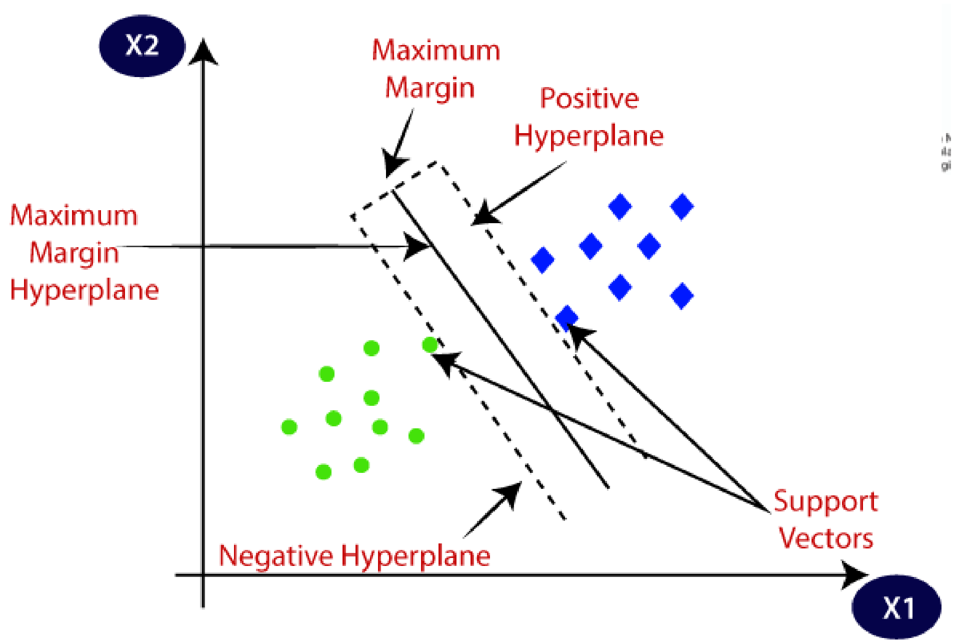


Figure 8: Support vector machine algorithm hyper-plane

Based on the nature of the hyperplane, Support Vector Machines (SVM) are classified into two types and they are linear and non-linear SVM.

- **Linear SVM:** It uses linear decision boundaries for the separation of the data points from different classes. The data can be precisely linearly separated and linear SVMs are found to be suitable. Because, a single straight line (in 2D) or a hyper-plane (in higher dimensions) can entirely divide the data points into their respective classes. A hyper-plane that maximizes the margin between the classes is the decision boundary.
- **Non-Linear SVM:** It can be used to classify the data which cannot be separated into two classes by a straight line (in the case of 2D). By using kernel functions, nonlinear SVMs can handle nonlinearly separable data. With this kernel function the original input data are transformed into a higher-dimensional feature space, where the data points can be linearly separated. A linear SVM is used to locate a nonlinear decision boundary in this modified space.

2. Convolutional Neural Network (CNN)

It is also known as ConvNet, CNN is a deep learning algorithm mainly used for object recognition, image classification, detection, and segmentation. CNN is made up of multiple layers including convolutional layers, pooling layers, Rectified Linear Unit and fully connected layers. The architecture of this ML is inspired from the visual processing of the human brain, and it will be well-suited for capturing hierarchical patterns and spatial dependencies within images. CNN has its ability to autonomously extract features at a large scale, translation-invariant characteristics, empowering them to identify and extract patterns and features from data irrespective of its variations or translation and thereby enhancing its efficiency. Wide variety of pre-trained CNN architectures are accessible with a top-tier performance and some them are VGG-16, ResNet50, Inceptionv3, and EfficientNet, so the models can be adapt new tasks with relatively little data through a process known as fine-tuning. The efficiency on picture categorization is evaluated using a variety of criteria. Among the most popular criteria's are Accuracy, Precision, Recall, F1 Score.

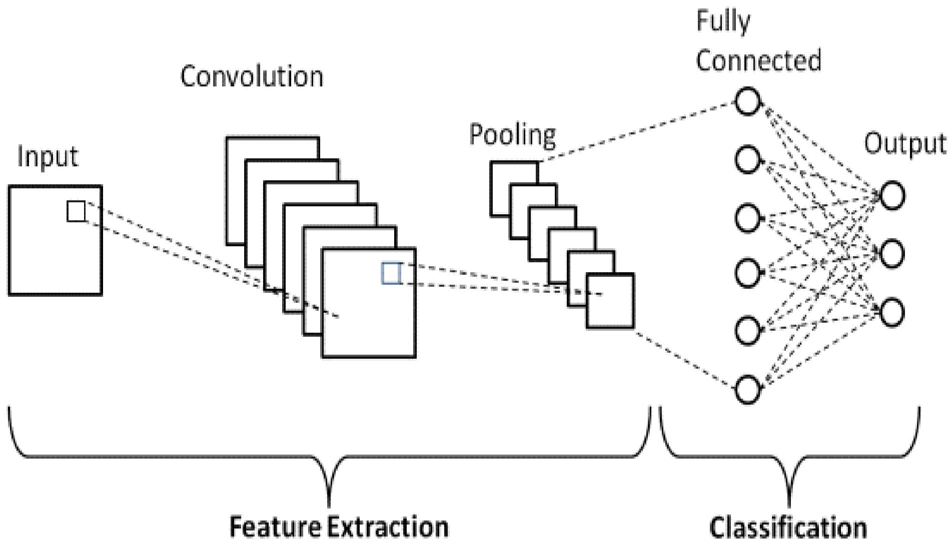


Figure 9: Convolutional Neural Network (CNN) Architecture.

3. Canny Edge Detection Technique:

It is a multistage process algorithm that starts from identification of the edges in an image by reducing noise, defining the Intensity Gradient of the Image, non-maximum suppression, thresholding and edge tracking hysteresis. Edge gradient and direction for each pixel is determined by image smoothening and filtered with a Sobel kernel in both horizontal and vertical direction to get the first derivative in both directions. Canny edge detection is the most commonly used algorithm in an image processing technique. Accurate edge, localization, Low error rate, Single response to edges, Robust to noise are some of the advantages over other techniques.

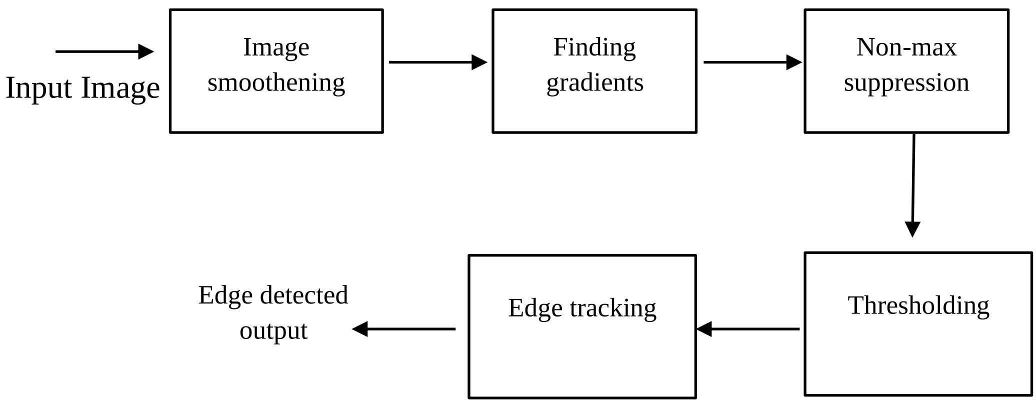


Figure 10: Canny edge detection process.

For the weather-aware pothole detection and image processing technique support vector machine

(SVM) machine learning can be used for the examination data for classification and regression and for its surface texture determination on image. Convolutional Neural Network (CNN) used for identifying and localizing the pothole and giving solutions to complex problems in image processing. Canny edge detection can be used in pothole detection and also for its image processing ability.

5.3 Discussion on Practical Implications and Challenge

5.3.1 Implementation Considerations for Road Authorities

The UAV-based pothole detection systems implementation faces numerous significant challenges in maintenance operations, regulations, data privacy concerns and workforce training.

- UAVs are available in different ranges of size from smaller to large commercial or military-grade aircraft. Its speed varies from 15m/sec to 100m/sec and it may have distinct flying characteristics. So there will be a difficulty in choosing the types of UAV based on size, speed and characteristics.
- There will be a Similarity between UAV and other flying objects like birds and airplanes. Due to its speed, flying pattern and dynamic behaviour, it will be difficult for a drone detection system because it may be not fast enough to miss a drone in video frames, monitoring and in precise identification.
- UAV may fly at different altitude levels; based on the size range it may differ between a few meters to many kilometres above the ground surface. The aerial platforms may be divided into higher altitude and lower altitude platforms. Due to its rapid deployment and low cost, the lower altitude platforms are mostly used for malicious purposes. Countermeasures for this purpose may become ineffective, harmful to collateral damage.
- One of the biggest problems in UAV-based technology is limited battery life. Lithium–Polymer (LiPo) batteries are the most commonly used battery type. Lithium–Iron–Phosphate (LiFePO4) batteries are believed to be safer and have a longer life cycle. Providing a big battery is not possible due to weight factor. It can fly in the air up to 30–40 min before landing, and swapping batteries might be trouble. Some factors like Temperature, humidity, altitude, and flight speed may affect the battery duration. And in UAV operation energy consumption reduction is critical.
- Due to varying weather conditions, depending on the location there will be more obstructions such as vegetation, buildings, terrain, surrounding noise and bad lighting conditions, UAV detection systems may get affected. And these environmental factors may result in imprecision, sensor disturbance, false positives or false negatives data. Thus,

it is an ongoing challenge to adapt and modify the detection and classification in algorithms to deal with various environmental circumstances.

- In a legal landscape drone use is complex and varies significantly across jurisdictions. In many countries, regulations are developed to address the safety, privacy, and security concerns associated with drones. These laws often mandate that drone operators avoid flying over private property without permission, and adhere to specific altitude limits. However in some cases, the devices are registered with the relevant authorities. Enforcement remains to be a challenge, as identifying and prosecuting violators will be difficult, given the anonymity that drones can provide their operators.
- Controlling operation in an aerial vehicle is a challenging factor. Skilled and more knowledgeable person is essential for operation. If not then it will be a difficult task for the researcher seeking the data. Improper operation may lead to miscommunication between the drone and the ground control station.
- UAVs have its limitations in operability due to critical concerns in terms of flight autonomy, path planning, flight time and limited payload carrying capability, as it is not recommended to load heavy objects.
- While landing the UAV following things need to be consider: when it is at air, position it at a point where it can descend, for landing roll back the throttle so that the drone slowly approaches the ground, when the UAV is about 3-5 cm above the ground before it touches the ground**,** then you should bring the throttle back to 0 so that it finishes descending.
- License problems may arise if the selected UAV size is more than 250grams. And consumer drones are not allowed to fly above 400 feet above ground level. This limit is set by regulatory authorities, such as the FAA in the United States, to ensure the safety of airspace and prevent conflicts with manned aircraft.
- Navigation has a strong impact on UAV flight control by its high-altitude, long-endurance capability. If the GPS signals are lost, finding the position of the UAV will become difficult.
- Drones tend to have more limitations in extreme weather. They are not suitable to use in extreme temperatures and controlling drones will be problematic and batteries will usually not function at freezing temperatures. The drone can provide accurate geographic data only in a favourable weather condition.
- Images acquired from the UAV may need ground truth technique for verification. And the validation processes the collected data are processed, analysed and used for the application.

5.3.2 Addressing Limitations and Future Directions

This study has a potential limitation. The acquisition of image is done by UAV-based technology for the monitoring of the pothole on a pavement and the image refinement is obtained by the application of a super resolution algorithm. For the monitoring data analysis, ground truthing technique and Statistical Analysis by regression technique are determined and compared for validation purposes. Investigation on impact of seasonal weather changes integrated with weather aware monitoring techniques. Proposed strategies and algorithms for weather-aware pothole detection, by the integration of image processing techniques and machine learning models trained on weather data.

Furthermore, the future research may focus on detailed study of freeze-thaw cycle impact on the pavement distress using advanced technologies, comprehensive review on the pothole detection for an extreme environmental condition and image distortion. Improvement in pothole detection accuracy by the combination of heterogeneous sensor systems. In UAV, flight endurance has a limited time due to its battery constrain.

Addressing this problem some innovative solutions are needed to be proposed. Detection of potholes by machine learning techniques for the texture accuracy. Comparative study on automated pothole detection with existing pothole detection systems for the improvement in real-time technology. Assessment of detected potholes based on estimations and measurements of depth and area for safety and road management maintenance.

Addressing the challenges by improving real-time performance, and exploring additional modalities and techniques for the pothole detection accuracy and efficiency enhancement.

Chapter 6
Conclusion and Future Research

6.1 Summary of Key Findings
6.1.1 Contributions to Road Infrastructure Monitoring

Road infrastructure is a fundamental foundation for the development of any nation. It plays a significant role in pounding the modern society and makes it more accessible and connected. It helps to promote fiscal benefit, communal bridging, safer transportation, regional development, positive environmental impact, improved quality of life and emergency services. With the increasing complexity of road infrastructure, ensuring their stability and performance has become a paramount. Density and quality are the two primary factors in road infrastructure to determine the competitiveness of the country. Regular road infrastructure monitoring and maintenance is essential to preserve and enhance the benefits. Lackadaisical monitoring and irregular maintenance cause irreversible deterioration of the road network by replacing or major repairs may appear just in a few years. The deterioration extends across a road system very quickly which results in soaring costs and a major financial impact on the economy and citizens.

Quality of the road is defined by monitoring process and its major indicators lie on road surface condition. Road anomalies like patching, bumps, cracking, potholes, rutting, depression, corrugation & shoving, stripping and other small defects on the surface can be used to characterize the quality of the road surface. Roadway potholes are one of the primary problems with transportation infrastructure. Accidents frequently occur because of these potholes. This research explores in the field of infrastructure monitoring by detecting the pothole on the road surface using an advanced technology of unmanned aerial vehicle (UAV) integrated with machine learning and proposed strategies for weather-aware monitoring techniques. Formation of potholes on roads is influenced by various seasonal weather changes which may depend on the factors like temperature, humidity, precipitation and sunlight. Most of the pothole formations are due to freeze-thaw cycle, contraction and expansion, structural integrity loss, erosion, moisture infiltration.

Detection of pothole defects can be done in conventional and advanced methods. Traditional methods of pothole detection, such as manual inspection and visual surveys, are time-consuming and labor-intensive, inaccurate, especially in large or remote areas. While UAV-based pothole detection is a promising new emerging technology that can help to improve road safety. These systems can use cameras, sensors, and machine learning algorithms for the automatic detection of potholes and it can be deployed in a variety of ways. It gives accurate information along with geo-spatial data, is easy, economical, consumes less time, and can integrate with any other technology for the refined result. In this study by examining the both methods in their performance of accuracy, efficiency and cost effectiveness, it concludes UAV-based technology is more adoptable from various aspects.

Weather-aware technique is nothing but atmospheric prediction relies on computer based models with advanced technology like machine learning, deep learning, Artificial intelligence (AI) which takes many atmosphere factors for considerations. Weather forecasting has a huge impact on road safety and operation. In general, the technique is designed to provide timely weather reports and surface road condition forecasts and it may be integrated with any other advanced tools. Using weather-aware techniques in a road defect detection it provides pavement heat balance models by predicting the road surface temperature and the depth of snow at each forecast lead-time. These forecasted road conditions can also be used for a well-organized road maintenance process.

According to a global status report, road safety accidents are the leading causes of injuries and deaths, approximately 1.25 million per year globally. WHO demanded all nations to achieve the ambitious target for road safety reflected in the newly adopted 2030 Agenda for Sustainable Development. As per 2023 report, death rates have fallen slightly by 1.19 million due to the effectiveness of enhanced road safety and its significant reductions in road traffic deaths can be made as proven measures are applied. The contribution of this study may help to achieve the target by reducing the road safety accidents and enhancing the proper road infrastructure management system.

6.1.2 Implications for Enhancing Pothole Detection Efficiency

Potholes are the greatest complications on the road and it may cause a lot of troubles in traffic. It can damage vehicles, make suspension systems worse, wrangle for drivers, delaying, traffic jams and cause accidents which leads to expensive repairs and more insurance claims.

Potholes go beyond inconvenience by causing serious problems which affect routine life. These road defect problems initiate a chain of issues from impacting transportation, safety, economic and infrastructure damage. The risky imperfect roads may lead to ample damages on vehicles by causing tire puncture, suspension problem, collateral damage, alignment issue and tire with repeated exposure may suffer by accelerating wear and tear results in often costly repair. The pothole on the road creates safety hazards for all road users. While navigating on the pitted surface it may increase the risk of collisions, swerving, loss of control in vehicles, consume more fuel, increased possibility of tripping or falling especially in an extreme weather condition. Potholes, cracks, bumps, rutting, depression, slippage and edge crack are the minute defects that occur on the road surface if it is not monitored, repaired and maintained properly it ultimately results in pavement structural disintegration. Large Economic strain on the Government shoulder due to the burden of repairing and maintaining road cost. Number of vehicles on the road increases and it makes the problem worse. With the frequent accident and increasing death rate it is important to detect the pavement defect with an automated system which can precisely find the problem with surface condition of the road.

By leveraging advanced technology like UAV-based technology for monitoring, remote sensing technology and Lidar technology for data collection, Artificial Intelligence & Machine Learning with advanced algorithms can be used to detect the defects in pavements with greater accuracy, precision, cost efficient and it may enhance the road safety, reduce potential accidents, increased productivity, increases the infrastructure longevity by enabling timely repair. In this research paper, experiment conducted for the detection of pothole on road surface is achieved by Unmanned Aerial Vehicle UAV based technology used for image Acquisition and the images are preprocessed and increase its quality with high resolution using Agisoft Metashape pro software and integrated with super resolution algorithm for better clarity and clear visualization. For evaluation and validation purposes ground truth technique is used by comparing it with the resulting 3D model. From the obtained result it may be useful for Gustave Eiffel University in the road management system.

6.2 Recommendations for Future Research

6.2.1 Further Investigation into Weather-Aware Monitoring Strategies

With the advent of advanced technology, the accuracy and reliability of weather prediction and road defect detection is enormously improved. Among these, artificial intelligence, machine learning and sensor based technologies are prominent in processing the data and identifying its complex pattern. Different types of algorithms are available for weather prediction such as support vector machine (SVM), artificial neural network (ANN), time series based recurrent neural network (RNN), multiple linear regression, decision tree, Convolution Neural Network (CNN), random forest, extreme gradient boosting and multilayer perceptron, etc., for weather-aware ML. Each algorithm has its own variables for the prediction factors like temperature, solar radiation, relative humidity and wind speed, etc. For road defect detection also several ML algorithms are using such as Naive Bayes, K-means clustering, Convolution Neural Network

(CNN), you only look once (YOLO), fuzzy C-means clustering, support vector machine (SVM), gradient boosting, random forest and so on.

Despite its advantage, machine learning faces more challenges in weather forecasting and defect detection. Some of them are: Limited training data – it requires vast amounts of data to train the mode but the availability of such data is limited. So the model can be biased which leads to inaccurate prediction; complex data –complicated data and multiple predicting variables for the interaction with each other by identifying the most critical variables for modeling and prediction; uncertainty – due to complexity of prediction and detection system, limited data, approximate measurement. And also it is hard to built accurate and effective prediction model when it is lack in clear interpretation which leads to failure of the system; real time data – it is essential to have a sophisticated data collection system capable of capturing and processing data in real-time. Because ML models require real-time data for précised prediction; interpretability – forecasting models are often complex and difficult to interpret. So certain predictions of the models are arduous and skeptical; data quality – providing exact, complete and up-to-date input data is delicate. Erroneous data can result in inaccurate prediction.

Advanced Sensor based weather-aware technologies are designed to measure a wide range of atmospheric conditions with enhanced accuracy, reliability, and efficiency. Each sensor is calibrated to provide exact readings and strategically placed at the weather station to capture the respective data of these variables. Sensors are functioning simultaneously by collecting and analyzing the data to understand current weather patterns, future condition prediction and provide critical information for various applications. Some of the sensors are advanced temperature sensor, wireless humidity sensor, digital barometric pressure sensor, ultrasonic anemometer and optical rain gauge. Two different functions based Sensors are used for road surface anomaly detections. Motion sensor - accelerometer, gyroscope, linear acceleration, gravity; position sensor - rotation, GPS, magnetometer.

Weather aware techniques and road defect detection techniques function in two different modes. For the integration of two techniques hybrid technology can be utilized for the required function. Furthermore, the scopes for future research in machine learning prediction methods are simulating datasets using statistical methods. Such synthetic data can provide a controlled environment for evaluation and validation of predictive models. For the robustness model enhancement Monte Carlo simulations or employing first-principle equations to generate realistic data methods can be used. Interpretability is a well-known drawback of machine learning models. A research may focus on incorporating statistical methodologies with machine learning algorithms for the actionable output. Physical modes are computationally intensive and machine learning can expedite these calculations. For the acceleration of physical mode, a simple surrogate model can be developed by intersecting traditional physical methods with machine learning. So that it may provide time sensitive real time analysis. In the road defect detection process, it may require a highly précised defect locator. Detecting multiple and small objects will be critical scenarios in advancing the field. For the calculation of size of road defects and road damage evaluation object segmentation algorithms can be used for its greater practicality and accuracy.

Limitation of sensor based technology depends on its installation and maintenance. Senors should be placed in a statistical position and require a routine calibration for an accurate data collection. It faces trouble in terms of data processing and storage due to its huge amount of data generation. By addressing its limitation, research may proceed in finding an innovative solution by lowering the usage of ground based sensors for collection of data. Additionally, AI algorithms and advanced data processing may provide rapid analysis of vast data with its enhanced speed and accuracy.

6.2.2 Integration of Advanced Technologies for Enhanced Monitoring

Road infrastructure management system is the primary means of defining, monitoring and maintaining the roadway features, condition, characteristics and providing analyzed data for decision making programs. For the implementation of a road management system (RMS) certain things need to be considered such as data for the road network, strategy for road maintenance with respect to economic optimum by simulating consequences of various alternatives, and developing methods for sound maintenance. Issues challenging in RMS are processing of collecting traffic, technical and road characteristics data and parameters in order to feed a wide database. Consistent parameters are required for the range of accuracy and implementation of data monitoring and updating have to be defined. Therefore, the initial design of the RMS is crucial to avoid further failures and the subsequent necessity to permanently restart the whole system.

Integrating UAV-based monitoring systems along with advanced technologies such as artificial intelligence, remote sensing and internet of things devices for the improvement of data-driven decision-making capability. Internet of things (IoT) technology is to connect any device or object to the internet by allowing them to collect and share data information which is remotely monitored and controlled. Remote sensing aids in assessing the road condition by providing real time data on traffic flow, congestion, and incidents. It enables authorities to make informed decisions, optimize traffic signals, improve overall efficient road safety and contribute to a more sustainable environment. Remote sensing systems are classified into two groups based on technical solution.

First is an active remote sensing system which emits radiation on the study object and measures the reflected amount of radiation such as Radar, Sonar, and Echo-sounder and the more recently added Lidar which use laser technology to emit and then collect reflections from the surface of the earth. And second one is a Passive remote sensing system which measures the existing radiation such as the reflected solar radiation from the earth's surface such as Photography, Digital photography, Scanning Mirror (MSS), and Push broom Scanner, etc. Global Positioning System (GPS) can function in both active and passive systems while Inertial Measurement Unit (IMU) can only function in an active remote sensing system. These two systems are commonly used in road infrastructure monitoring. Artificial intelligence (AI) based systems can use image recognition and machine learning to identify potholes, cracks, bumps, and other road hazards. And it enables analysis of the large volume of data for the improved road condition monitoring system with more efficient maintenance, and enhancing overall road safety.

Data is collected from the remote sensing technology while the artificial intelligence (AI) component has the accurate incoming data needed to extract valuable insights and then it makes intelligent decisions through its advanced algorithms. By combining AI with advanced algorithms along with remote sensing it becomes a powerful tool for collecting and analyzing data. For the integration of technology, IoT devices are embedded with AI and remote sensing systems to collect, process and analyse dynamic real-time data and are related to a central gateway, thus forming a comprehensive sensory network. But all sensors are different and different IoT applications require different types of sensors. For RMS active and passive sensor, contact and non-contact sensor, absolute and relative sensor, analog and digital sensor can be used with the properties of accuracy, resolution, sensitivity, linearity, hysteresis, drift and precision. AI is becoming increasingly important in the Internet of Things (IoT) ecosystem and AI sensors can enable IoT devices to learn from their environment and make decisions based on that learning, without human intervention.

Unmanned Aerial Vehicle UAV-based monitoring has become an attractive solution due to its mobility, cost efficiency, broad view range and with a lot of advantages including its accessibility and connectivity with other technologies. Integrating UAV- based technology with artificial intelligence, remote sensing and internet of thing (IoT) device, this collaboration results in enhanced automation, facilitates predictive analyses, personalization, cost efficient, fosters adaptability, optimized operations, improved resource efficiency, security concern, complex integration and improved user experience. In the Road management system (RMS), the result obtained from multiple integrated technologies monitoring road defects and maintenance can be planned in an organized manner for a proper pavement system.

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