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ARTICLE

Pothole Detection Based on UAV Photogrammetry

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ABSTRACT

Potholes are the most prevalent type of structural defect found on roads, caused by aging infrastructure, heavy rains, heavy traffic, thin or weak substructures, and other factors. Regular assessment of road conditions is essential for maintaining and improving road networks. Current techniques for identifying potholes on urban roadways primarily rely on public reporting, such as hotlines or social networking websites, which are both time-consuming and inefficient. This study aims to detect potholes using Unmanned Aerial Vehicles (UAVs) images, enabling accurate analysis of their size, shape, and location, thereby enhancing detection efficiency compared to conventional methods. It compared area and volume measurements of potholes derived from UAV models with those obtained through traditional methods, revealing discrepancies and highlighting UAVs' potential for providing more accurate data with appropriate settings. The study found measurement errors ranging from 90 to 8200 cm^2 in area and 2000 to 31,000 cm^3 in volume, emphasizing the need for careful data handling in assessments. This study demonstrates UAV technology's effectiveness in pothole detection, providing insights that support the adoption of aerial photogrammetry for road maintenance. This approach has the potential to improve efficiency in infrastructure management. By appropriately adjusting altitude settings and parameters based on pothole size and depth, UAVs can detect potholes effectively. To achieve more accurate results, the study recommends analyzing a larger number of potholes rather than limiting the focus to a single pothole.

KEYWORDS

Aerial photogrammetry; 3D modelling; digital elevation model; volume estimation

1 Introduction

Roads, as an essential component of national infrastructure, play a crucial role in the development of every country. They facilitate transportation, commerce, and connectivity, forming the backbone of both urban and rural economies. Regular evaluation of road conditions is necessary for the maintenance and improvement of the road network. Poor road maintenance can lead to deteriorating conditions, making roads dangerous for both drivers and pedestrians. The failure to address issues such as potholes can cause costly damage to vehicles, increase accident risks, and result in higher repair expenses over time.

Manual approaches to road inspection, while common, are labor-intensive, expensive, and prone to human error. Human evaluation often involves subjectivity and variability in skill and experience. Inconsistent assessments can lead to ineffective maintenance strategies, compromising road safety. Identifying and assessing potholes, one of the most common forms of road damage, is particularly challenging with traditional methods. Therefore, a system for the automatic identification and assessment of potholes is required to improve the monitoring of road conditions [1].

Potholes are a persistent issue worldwide. They pose significant hazards, not only damaging vehicles but also endangering lives. The costs associated with pothole repair are substantial, with some countries spending millions annually to address road defects. For instance, over 2 million potholes were repaired in the UK in 2017 alone, at an estimated cost of over £120 million [2]. Despite these efforts, potholes continue to appear, primarily because the underlying causes of road wear, such as traffic load, poor weather, and drainage issues, are not fully addressed. Potholes often originate from small, barely visible cracks in the road surface. Over time, water infiltrates these cracks, weakening the structure beneath. When vehicles pass over these weakened areas, the cracks expand, eventually leading to potholes.

Urbanization and industrialization in Central Vietnam have accelerated surface heat impacts, particularly in Da Nang City and Quang Nam Province. The study found a consistent rise in temperature, evaporation, and relative humidity in Da Nang, while Quang Nam exhibited an inverse relationship between temperature and humidity due to urbanization. Since 2000, temperatures in Da Nang have risen by 0.71°C, with urban areas experiencing higher temperatures due to reduced vegetation and increased concrete-based infrastructure, which worsens road deterioration. Additionally, increased rainfall and temperature, driven by climate change, contribute to road damage and flooding. These findings provide a scientific basis for sustainable land-use management and raise awareness among regional decision-makers [3].

In cold and wet climates, water plays a significant role in the formation of potholes. During colder months, water seeps into cracks in the asphalt and freezes, expanding and exerting pressure on the road surface. When the ice thaws, the road is left structurally compromised. The continuous passage of vehicles over these weak spots further loosens the material, eventually causing the surface to collapse into a pothole [4].

A pothole is essentially a depression in the road surface, most commonly found in asphalt pavements. It occurs when traffic and environmental factors weaken the underlying support structure. The edges of potholes are often sharp, and they can vary significantly in size. Potholes are more prevalent on roads with thinner asphalt layers, particularly those less than 100 mm (4 inches) deep (Fig. 1) [5]. Once a pothole forms, it tends to grow as traffic displaces the loosened material, making repair more urgent and costly.

While pothole repairs are typically reactive, requiring crews to patch existing damage, this approach is not sustainable. Patching potholes is a temporary fix, often resulting in a recurrence of the problem due to a failure to address the underlying issues. Proper road maintenance should ideally involve a more comprehensive strategy, addressing both the surface and the sublayers of the road. Full-depth repairs, which replace both the surface and the foundation, are far more effective in preventing pothole formation. However, the cost and logistical challenges of full-depth repairs mean they are infrequently performed. As a result, many road repairs remain *ad hoc*, focusing solely on surface flaws without tackling deeper structural issues [6–9].

(a) (b)

Figure 1: Road defect; (a) deep pothole, (b) cracking road [5]

The reliance on public reporting systems, such as hotlines or social media, for pothole detection is both time-consuming and inefficient [10,11]. These methods place the burden on drivers and residents to identify and report potholes. Furthermore, the subjective nature of reports can lead to inconsistent prioritization of repairs. To improve the efficiency of road maintenance, there is a need for a more systematic and technology-driven approach to pothole detection.

Recent advances in technology, particularly in geospatial and imaging systems, have the potential to revolutionize how potholes are detected and repaired. One such approach is the use of deep learning algorithms and image processing techniques to automatically identify road defects. By mounting cameras on vehicles, images of road surfaces can be captured in real-time. These images are then processed using object detection algorithms, which can accurately identify potholes based on their shape, size, and location [12].

An even more innovative solution involves the use of Unmanned Aerial Vehicles (UAVs), commonly known as drones, for road monitoring. UAVs are equipped with high-resolution cameras that can capture detailed images of road surfaces from above. These images can be processed using photogrammetry and computer vision techniques to reconstruct 3D models of road defects [13]. By generating a Digital Surface Model (DSM) and a Digital Elevation Model (DEM) of the road, it is possible to accurately measure the depth and volume of potholes. This data provides a more comprehensive understanding of the road's condition, enabling authorities to prioritize repairs based on the severity of the damage.

One study demonstrated the effectiveness of UAVs in pothole detection by creating 3D models of potholes and validating the results with *in situ* measurements. The analysis compared the size and volume of potholes obtained through different methods with those measured directly on-site [14]. The results indicated that UAV-based detection was highly accurate, particularly when altitude and camera parameters were appropriately adjusted based on the size and depth of the potholes. However, the study emphasized the importance of analyzing a large number of potholes to ensure the results are generalizable.

In addition to UAVs, stereo vision systems are another promising technology for pothole detection. Stereo vision utilizes two cameras mounted side-by-side to capture images of the road from slightly different perspectives. By comparing the two images, it is possible to generate a depth map that highlights depressions in the road surface. This method has proven effective in detecting potholes, as it can accurately measure both the size and depth of defects [15]. Moreover, stereo vision systems are relatively low-cost and can be easily integrated into existing road maintenance vehicles.

Another method involves deep learning-based approaches, which use convolutional neural networks (CNNs) to analyze road images for pothole detection. These algorithms can be trained on large datasets of road images, allowing them to recognize potholes with high accuracy. One such system was designed to detect potholes using images captured by smartphones mounted on vehicles. The system identified potholes in real time and uploaded the location data to a cloud-based mapping system. This feature allows drivers and road authorities to be notified of the pothole's presence, facilitating quicker repairs [16–19].

3D pothole image reconstruction is another innovative technique that provides authorities with detailed visualizations of road defects. By combining multiple 2D images taken from different angles, the algorithm can reconstruct the pothole's shape and depth in 3D [20–22]. This information helps assess the severity of the pothole and prioritize repair efforts. Additionally, the 3D models can be integrated into geospatial mapping systems, allowing for more efficient road maintenance planning [23–27].

In conclusion, pothole detection is a critical aspect of road maintenance, and recent advancements in geospatial and deep learning technologies offer promising solutions. UAVs, stereo vision systems, and deep learning-based algorithms provide accurate, efficient, and cost-effective methods for detecting road defects. By automating the process, these technologies reduce reliance on manual inspections and public reporting, ensuring potholes are identified and repaired promptly. As these methods continue to evolve, they hold great potential for improving road safety and reducing maintenance costs, contributing to more resilient infrastructure systems worldwide.

2 Materials and Method

The experimental area selected for this study is located around the Universiti Teknologi MARA (UiTM) campus in Shah Alam, Malaysia (Fig. 2), specifically in regions frequently impacted by heavy vehicle traffic. This area has been identified as ideal for pothole detection research due to the recurring presence of road surface damage, including multiple potholes of varying sizes and depths. These conditions primarily result from continuous usage by service and maintenance vehicles, which place substantial strain on the road infrastructure.

Figure 2: Map of UiTM Shah Alam, Selangor

For precise reference, the primary study locations encompass key road sections within the campus, including Jalan Ilmu and Jalan Cendekia. The coordinates of these focal areas range approximately from 3.0672° N, 101.5012° E to 3.0695° N, 101.5048° E. These locations exhibit a diverse array of pothole formations, making them well-suited for testing UAV-based 3D reconstruction models.

The UAV imaging process will be conducted along these specified routes, capturing high-resolution images at various altitudes to ensure detailed data acquisition. The captured images will facilitate the generation of 3D models for each pothole, providing a comprehensive dataset for analysis and validation against ***in situ*** measurements. This approach enables the study to focus on real-world, traffic-related wear patterns within an accessible and well-documented urban area, enhancing both the applicability and reliability of the research findings. Fig. 3 depicts the study's methodology, structured into four phases: Preliminary Study, Data Acquisition, Data Processing, and Data Analysis.

2.1 Preliminary Study

The preliminary study serves as the initial stage in defining the methodology for developing the research question related to this study. This stage is essential for identifying key considerations in data collection and processing. It emphasizes site selection, equipment preparation, and software selection.

2.2 Data Acquisition

This phase outlines the detailed steps for on-site data acquisition, including drone operation and image data collection. Efficient execution of this process is essential, as various challenges can arise at critical moments. Images of the potholes will be captured using a Multi-Rotor DJI Phantom 4 Pro drone. Preparation involves verifying the functionality of the drone's camera and connecting the DJI Phantom 4 controller to an iPad, which is equipped with the DJI GO 4 application for image capture. The UAV controller must be set up to control the drone's movements during data collection. Once the controller is connected to the iPad, live images of the potholes can be viewed on the iPad's screen. The pothole images will be captured from two distinct altitudes—3 and 5 m—with an overlap of approximately 80%.

2.3 Data Processing

Once the data is collected, it is processed and transformed into usable information. For this study, the data processing will focus on reconstructing a 3D model of the pothole using Pix4D Mapper Software. The process begins by creating an orthophoto from the images captured using the UAV. Next, the Digital Surface Model (DSM) and Digital Elevation Model (DEM) will be generated to determine the height values of the orthophoto. After creating the orthophoto, DSM, and DEM, the 3D reconstruction of the pothole model will proceed using ArcGIS software. This step involves digitizing, masking, and generating the final 3D model of the pothole.

Before starting the 3D modeling, the orthophoto for all captured potholes must be generated. Pix4D will be used to ensure the orthophoto's accuracy, ensuring the selected area is not randomly chosen, based on the DEM displayed in ArcGIS. Following the completion of the orthophoto, the generation of the Triangulated Irregular Network (TIN) and DEM will proceed, along with masking the desired area. The 3D model of the pothole will then be created and analyzed. Finally, the volume and area of the pothole will be calculated using the Surface Volume tools in Arc Toolbox.

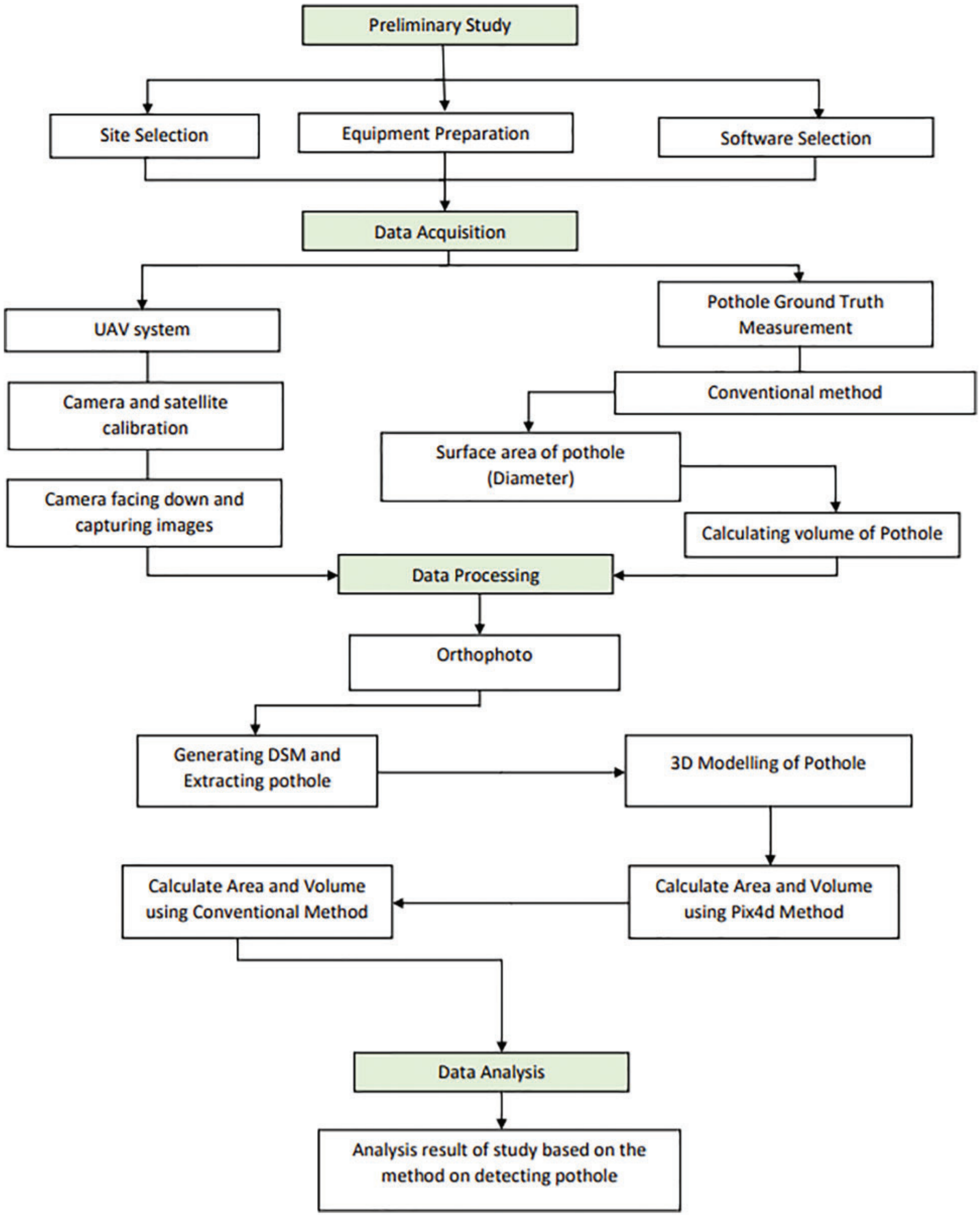


Figure 3: Flowchart of methodology

3 Results and Analysis

This study will collect two types of data for analysis. The first type is UAV data, which will be used for image processing. The outputs from Pix4D software will include the orthophoto, Digital Surface Model (DSM), and Digital Terrain Model (DTM), generated through image matching. These outputs will then be processed in ArcGIS software to reconstruct the 3D model of the pothole. ArcGIS will produce results such as digitizing and masking the pothole layer using the orthophoto and DSM from Pix4D. The 3D pothole model will be obtained by opening the masked pothole layer in ArcScene. ArcGIS will calculate the area and volume of the pothole as the processing continues.

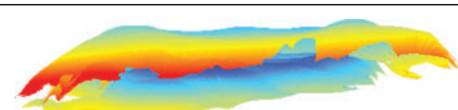
In addition to the software-based methods, conventional data collection will involve measuring the area of the pothole using grid paper and its volume using a measuring container. This manual method will provide comparative results for evaluating the accuracy and precision of both the software-based and conventional methods.

To calculate the pothole's area using grid paper, the pothole will be outlined on a sheet of grid paper placed directly over or next to it. Each square on the grid represents a specific area, allowing for easy estimation of the pothole's dimensions. By counting the number of full squares covered by the pothole and estimating the area of any partial squares, the total area can be calculated. This method offers a visual representation of the pothole's size, helping ensure accuracy by allowing careful measurement of its irregular shape.

For volume measurement, a conventional method involves filling the pothole with sand and measuring the amount used. The sand is carefully poured into the pothole until it is filled to the brim. Afterward, the sand is collected in a measuring container to determine the total volume. The volume of sand used directly correlates with the pothole's volume, providing a tangible measure that can be compared against results from software-based methods. This combination of grid paper for area calculation and sand for volume measurement offers a reliable manual approach to validate the findings from digital methods.

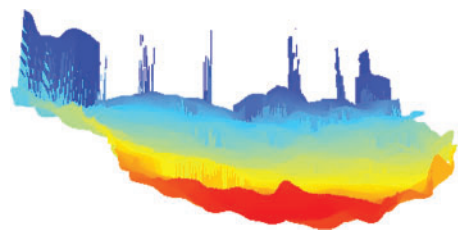
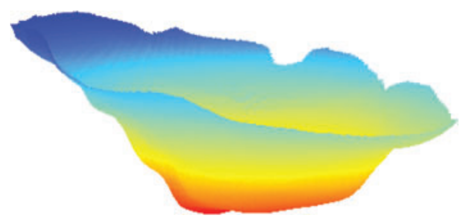
All images captured by the Multi-Rotor DJI Phantom 4 Pro drone were used to generate the study's 3D pothole model. These images included five different potholes, each taken from varying altitudes (Table 1). This section will detail the outcomes, including the DSM, DTM, and the 3D pothole model. Following this, an accuracy evaluation will compare the area and volume measurements obtained from the 3D model with those from manual calculations using grid paper and a measuring container.

Table 1: The result of the 3D model of the pothole

Type	Altitudes	3D Model of Pothole from ArcScene
Pothole 1	3 m	
Pothole 1	5 m	
Pothole 2	3 m	

(Continued)

Table 1 (continued)

Type	Altitudes	3D Model of Pothole from ArcScene
Pothole 2	5 m	
Pothole 3	3 m	
Pothole 3	5 m	
Pothole 4	3 m	
Pothole 4	5 m	
Pothole 5	3 m	
Pothole 5	5 m	

3.1 Calculating of the Area and Volume of the Pothole

The area of the digitized pothole can be examined by opening the attribute table in Arc Toolbox. The volume of the pothole can be estimated using the Surface Volume tools in Arc Toolbox, with the previously masked polygon used for calculation. The results will be displayed in meters in the attribute table. To analyze the area, the results will be converted to square centimeters. Tables 2 and 3 present the results obtained from the processing, detailing the area and volume, respectively.

Table 2: Area of each pothole from Pix4D mapper software

Type	Altitudes	Pix4D (cm^2)
Pothole 1	3 m	4293.47
Pothole 1	5 m	2054.23
Pothole 2	3 m	7331.60
Pothole 2	5 m	6225.49
Pothole 3	3 m	953.68
Pothole 3	5 m	9575.62
Pothole 4	3 m	629.53
Pothole 4	5 m	983.92
Pothole 5	3 m	849.27
Pothole 5	5 m	381.75

Table 3: Volume for each pothole from Pix4D mapper software

Type	Altitudes	Pix4D (cm^3)
Pothole 1	3 m	10,436
Pothole 1	5 m	38,018
Pothole 2	3 m	15,624
Pothole 2	5 m	1051
Pothole 3	3 m	11,970
Pothole 3	5 m	43,746
Pothole 4	3 m	7768
Pothole 4	5 m	3605
Pothole 5	3 m	10,707
Pothole 5	5 m	2954

3.2 Accuracy Assessment

The accuracy assessment for this study will compare two key dimensions of the pothole: surface area and volume. Errors will be evaluated by comparing these dimensions between the conventional and software-based methods. Tables 4 and 5 present the comparisons of area and volume obtained from both methods.

Fig. 4 illustrates the differences between conventional area measurement and the Pix4D software, while Fig. 5 depicts the differences between conventional volume measurement and the Pix4D software. The results show a difference in error between measurements taken at three meters and five meters altitude. For area measurement, the mean error at three meters is 870.014 cm^2, while at five meters it is 2532.97 cm^2.

Table 4: Comparison of area between conventional and Pix4D

Type	Altitudes	Conventional (cm^2)	Pix4D (cm^2)	Error (cm^2)
Pothole 1	3 m	4744.60	4293.47	451.13
Pothole 1	5 m		2054.23	2690.37
Pothole 2	3 m	4563.76	7331.60	2767.84
Pothole 2	5 m		6225.49	1661.73
Pothole 3	3 m	1464.59	953.68	510.91
Pothole 3	5 m		9575.62	8111.03
Pothole 4	3 m	884.41	629.53	254.88
Pothole 4	5 m		983.92	99.51
Pothole 5	3 m	483.96	849.27	365.31
Pothole 5	5 m		381.75	102.21

Table 5: Comparison of volume between conventional and Pix4D

Type	Altitudes	Conventional (cm^3)	Pix4D (cm^3)	Error (cm^3)
Pothole 1	3 m	7150.173	10,436	3285.83
Pothole 1	5 m		38,018	30,867.8
Pothole 2	3 m	13,750.232	15,624	1873.77
Pothole 2	5 m		1051	12,699.23
Pothole 3	3 m	2982.501	11,970	8987.5
Pothole 3	5 m		43,746	40,763.5
Pothole 4	3 m	1550.520	7768	6217.48
Pothole 4	5 m		3605	2054.48
Pothole 5	3 m	884.362	10,707	9822.64
Pothole 5	5 m		2954	2069.64

The analysis of pothole area measurements obtained via UAV imaging at two different altitudes (3 and 5 m) revealed varying accuracy influenced by the characteristics of each pothole. For Potholes 1 and 3, measurements at 3 m demonstrated superior accuracy, indicated by significantly lower error values compared to those at 5 m. This suggests that the closer proximity allowed for more precise capture of the pothole's geometry, minimizing distortions and enhancing detail. Conversely, Potholes 2, 4, and 5 showed better accuracy at 5 m. The reduced errors at this altitude indicate that, for these specific potholes, the distance from the UAV did not compromise the quality of the data. This finding underscores the importance of evaluating individual pothole characteristics, as certain features may make higher altitudes more suitable for accurate measurements. Overall, the findings suggest there is no one-size-fits-all altitude for UAV-based pothole detection; rather, the optimal altitude depends on the geometry and environmental context of each pothole.

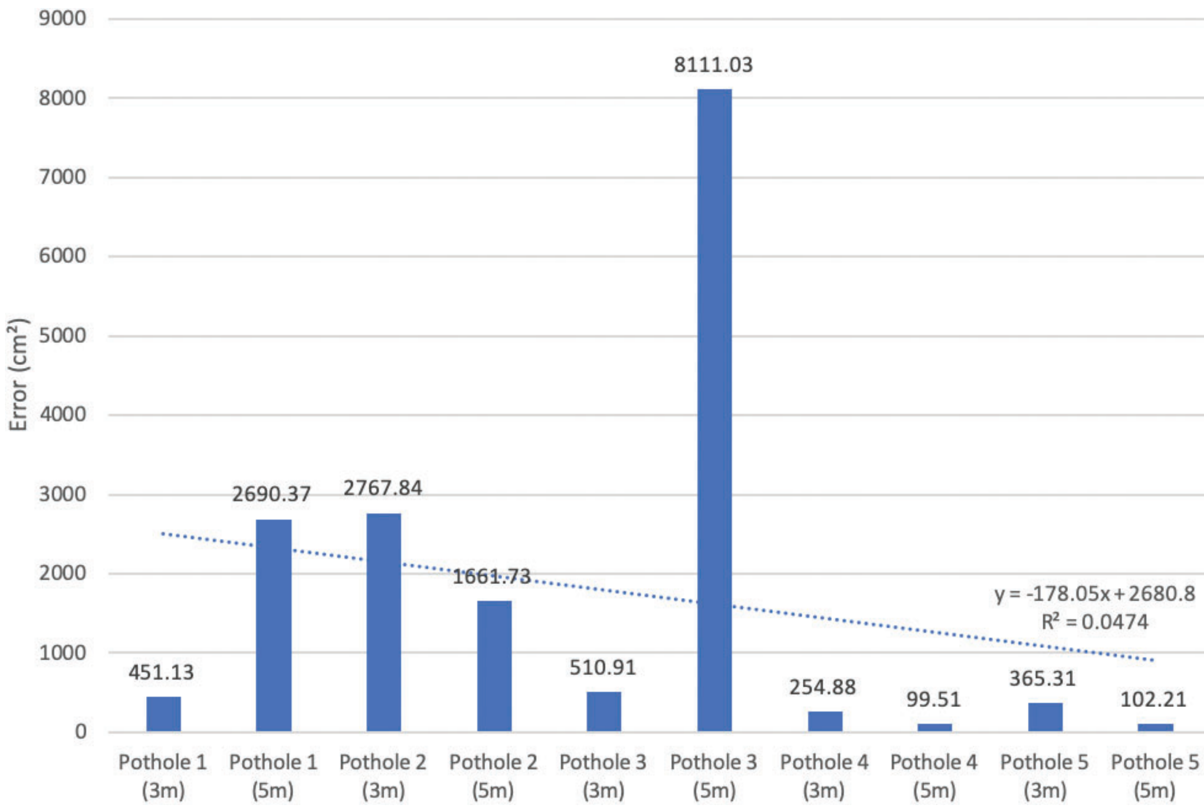


Figure 4: Differences of area measurement between conventional method and Pix4D software

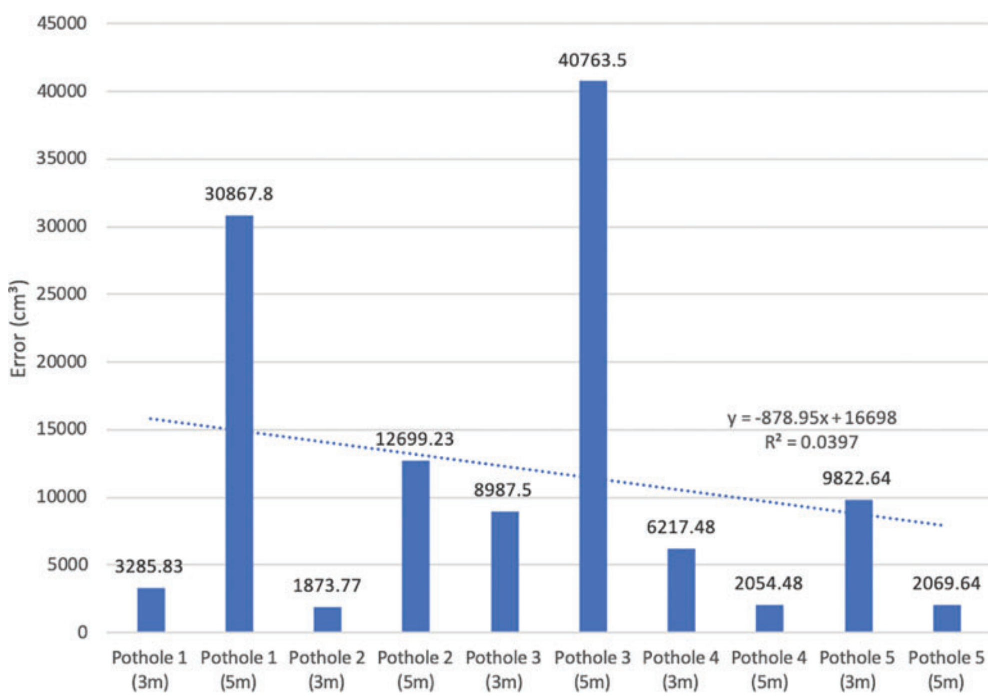


Figure 5: Differences of volume measurement between conventional method and Pix4D software

Similarly, for volume measurement, the mean error at three meters is 6037.444 cm^3, compared to 17,690.884 cm^3 at five meters. The analysis of volumetric measurements of potholes captured via UAV imaging at altitudes of 3 m and 5 m provided critical insights into the accuracy of data collection methods. By comparing the conventional measurements with those obtained from Pix4D software, patterns emerged regarding the influence of altitude on measurement precision across different potholes. For Potholes 1, 2, and 3, measurements at 3 m consistently demonstrated superior accuracy, indicated by lower error margins. This suggests that closer proximity to the potholes allows for better detail capture and reduces potential distortions, enhancing measurement fidelity. The results show that operating at this altitude is generally beneficial for effective UAV imaging, especially for pothole detection. Conversely, Potholes 4 and 5 showed improved accuracy at 5 m, with lower error margins than their respective 3-m measurements. This finding highlights that certain pothole characteristics may allow for more reliable data collection even at higher altitudes. Consequently, it is important for practitioners to recognize that optimal altitude settings may vary based on the unique features of each pothole. Overall, this study emphasizes the need for a tailored approach when determining altitude settings for UAV imaging. While lower altitudes typically yield better results for many potholes, certain conditions, as observed with Potholes 4 and 5, may require higher altitude measurements to achieve greater accuracy.

4 Conclusion

The creation of a 3D pothole model for road surfaces represents an innovative approach to accurately depicting and analyzing potholes. This model utilizes 3D technology to produce a virtual representation of potholes, offering a detailed view of their size, shape, and location. The study included five different potholes at two distinct altitudes, resulting in a total of ten models. To create these 3D models, the pothole areas were extracted and masked using the Digital Surface Model (DSM) for each orthophoto obtained from Pix4D Mapper software during data processing. Among the results, Pothole 5 at an altitude of 5 m was the only one that did not produce an ideal 3D model. This discrepancy may be attributed to errors occurring during various processing steps, such as the creation of the orthophoto, digitizing, or layering. In contrast, the remaining pothole models were accurately represented as 3D models without significant issues.

This study validates the extracted pothole results by comparing measurements obtained from ArcMap software with actual ground measurements. The results showed significant variation in the area measurements across the five potholes at two different altitudes. The error range for the area measurements varied from 90 to 8200 cm^2. Specifically, Pothole 4 at 5 m altitude exhibited the smallest error of 99.51 cm^2, while Pothole 3 at the same altitude had the largest error of 8111.03 cm^2. This variation indicates that errors could originate from either the conventional measurement method or the data processing steps. For volume measurement, the error ranged from approximately 2000 to 31,000 cm^3. This discrepancy suggests that errors in volume measurement might stem from mistakes during the manual conventional data collection, as the volume had to be calculated manually. It is also possible that errors were introduced during the processing steps, such as the creation of the orthophoto or the digitization of the pothole polygon. In summary, the observed discrepancies in both area and volume measurements highlight potential sources of error in both conventional and software-based methods, necessitating careful consideration and validation of both approaches.

In conclusion, the analysis of area and volume measurements for potholes using UAV imaging revealed that proximity significantly impacts measurement accuracy. Results indicated that lower altitudes (3 m) generally yielded more reliable data for Potholes 1, 2, and 3, while specific characteristics of Potholes 4 and 5 allowed for improved accuracy at a higher altitude (5 m). However, significant discrepancies in volumetric calculations, particularly at 5 m, highlight potential flaws in the measurement methodology and challenges in generating effective Digital Surface Models (DSMs) within the pits. These findings underscore the necessity for optimizing altitude settings and refining measurement techniques in future studies to enhance the precision of UAV-based pothole detection. Overall, this research demonstrates the promising potential of UAV technology for effective infrastructure monitoring while also pointing to the importance of addressing methodological limitations to improve the reliability of results in practical applications.

Aerial photogrammetry using UAVs has proven to be a convenient and effective method for modeling potholes. The study demonstrated that potholes can be accurately detected when the altitude settings and parameters are appropriately adjusted to the size and depth of the potholes. Effective planning is crucial for successful data acquisition. Ensuring that all necessary data is collected accurately and without issues during the data processing stage can prevent the need for repeated on-site data collection. Therefore, meticulous planning and preparation during the data acquisition phase are essential for achieving precise and reliable outcomes in pothole modeling.

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Availability of Data and Materials: The data and materials used in this study are not publicly available due to government policy but may be requested from the corresponding author under certain conditions.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

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