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Assessing Precision and Dependability of Reconstructed Three-Dimensional Modeling for Vehicles at Crash Scenes using Unmanned Aircraft System

Akmal Jauhari Jalal[1], Mohd Farid Mohd Ariff[2,*], Ahmad Firdaus Razali[1], Razak Wong Chen Keng[3], Mohamad Ariff Wook[3], Mohamad Ikhwan Idris[3]
[1]Geospatial Imaging & Information Research Group (GI2RG), Faculty of Built Environment & Surveying, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[2]UTM-PDRM Geospatial Forensics Satellite Laboratory, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[3]Geodelta Systems Sdn. Bhd., No. 22, Jalan SS20/11, Damansara Utama, 47400 Petaling Jaya, Selangor, Malaysia
*Corresponding author: mfaridma@utm.my

***Abstract* –** This study focuses on the accuracy assessment of 3D reconstructions of crime scenes using Unmanned Aircraft Systems (UAS) and Terrestrial Laser Scanners (TLS) data for forensic crash investigation. Forensic crash investigation involves meticulously analyzing physical evidence, vehicles, and human factors in road collisions to determine the sequence of events. Preserving the original state of the crash scene before cleaning is essential for accurate forensic analysis. However, this preservation process can disrupt normal activities and demand considerable time. Geomatic technology, specifically UAS or drones, offers a potential solution for efficient and precise forensic mapping. The application of UAS technology enables swift data collection, leading to cost savings, enhanced safety, and data utilization. This study aims to assess the suitability of UAS techniques for forensic mapping, encompassing both relative and absolute accuracy. This research uses a UAS to rapidly and comprehensively capture evidence from a simulated crash site using predefined flight paths. The acquired image data is then processed utilizing Agisoft Metashape software, generating a detailed 3D model of the crash scene. This model can be enriched with annotations, measurements, and pertinent information. A comparative analysis is performed by preparing a table that contrasts the absolute and relative accuracy of UAS-collected data with that obtained from TLS, which serves as a benchmark. The results reveal that the UAS demonstrates a relative accuracy Root Mean Square Error (RMSE) of approximately ±4.1 cm compared to TLS. Concerning absolute precision, the UAS-produced RMSE values are determined as ±0.20719 for the X coordinate, ±0.164 for the Y coordinate, and ±0.001584 for the Z coordinate compared to GNSS data, which functions as the benchmark. The utilization of UAS technology offers a non-invasive measurement approach that eliminates direct physical contact between the operator and the documented object. This non-intrusive method ensures the preservation of the original scene characteristics and has shown its superiority over conventional approaches in managing crash scenes. Overall, this study underscores the potential of UAS technology in accurately reconstructing crime scenes for forensic investigation purposes.

Keywords *– Photogrammetry, Forensic Mapping, Unmanned Aircraft System (UAS)*

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1.0 Introduction

Traffic accidents significantly impact public safety, causing numerous fatalities and injuries worldwide every year. In Malaysia, for instance, motor vehicle crashes resulted in 567,516 road accidents in 2019 (Amiruddin et al., 2023). Traditional forensic investigations of these accidents have relied on manual measurements and photographs, which are time-consuming, imprecise, and may not capture the complete scene. However, the emergence of unmanned aircraft systems (UAS) or drones has provided a promising solution for enhancing forensic investigations of traffic accidents (Adnan et al., 2020). UAS can capture high-resolution aerial images and videos, creating precise 3D models of the accident scene. These models offer a comprehensive overview of the accident, assisting investigators in identifying crucial evidence that may have been overlooked using traditional methods. Furthermore, UAS can access difficult-to-reach areas, improving data collection.

Despite its potential, using UAS in forensic investigations is still an evolving field and faces particular challenges. There is a lack of standardized protocols for UAS data collection and analysis, resulting in inconsistent data and hindering the comparison of results. Privacy concerns related to capturing images and videos of private property and individuals must also be addressed. In Malaysia, the Civil Aviation Authority of Malaysia (CAAM) has established regulations governing UAS use in forensic investigations, mandating operators to obtain a remote pilot certificate and adhere to safety guidelines (Civil Aviation Authority of Malaysia, 2016).

Forensic mapping, which involves documenting the location and position of physical evidence, plays a crucial role in investigations. It assists in reconstructing events, identifying suspects, and solving various cases such as homicides, burglaries, and hit-and-run accidents. Forensic mapping also aids in recognizing crime patterns and trends, enabling law enforcement agencies to develop effective strategies. Courts recognize forensic maps as admissible evidence in criminal trials. This study aims to utilize unmanned aerial systems (UAS) to generate a comprehensive 3D model of a crash scene using image data and subsequently evaluate the accuracy of the resulting model through rigorous analysis. Combining UAS and forensic mapping can revolutionize forensic investigations by providing more accurate and comprehensive data, thereby assisting in crime-solving and prevention efforts.

2.0 Literature Review

This section aims to enhance comprehension of the latest findings derived from diverse sources such as research papers, articles, books, websites, and other relevant materials. The chapter will delve into photogrammetry, unmanned aircraft systems (UAS), and the utilization of UAS in forensic investigations for road accident reconstruction.

2.1 Photogrammetry

Photogrammetry is a comprehensive discipline encompassing the art, science, and technology employed to obtain precise information about physical objects and the surrounding environment. It involves the analysis, measurement, and interpretation of photographic images and other electromagnetic energy patterns (Prosser-Contreras et al., 2020). Photogrammetry has transformed from analogue to digital techniques, enabling the accurate measurement of three-dimensional objects and terrain characteristics from two-dimensional images.

There are two primary types of photogrammetry: aerial and terrestrial. Aerial photogrammetry captures visible light waves and near-infrared technology, while terrestrial photogrammetry is used for close-range object distances. In aerial photogrammetry, vertical aerial photographs are preferred, preferably in stereo pairs, although single photographs can still provide reasonable measurements if the scale is known. The interpretation of these photographs can be transferred to maps through manual drawing or digitization. Softcopy photogrammetry techniques incorporate analytical models for coordinate calculations (McGlone et al., 2004).

Photogrammetry is a versatile methodology that employs a range of processes, including engraving, measuring, and interpreting photographic images and radiation patterns, to obtain reliable information about physical objects and the environment (Prosser-Contreras et al., 2020). By utilizing automated techniques such as interest-point detection, Structure from Motion algorithms, and dense image-matching, photogrammetry can enhance and expedite the acquisition of geometric information related to physical objects. Through photogrammetric data processing, a three-dimensional model can be created, enabling precise measurements and detailed visualization of objects and terrain.

2.2 Unmanned Aircraft System (UAS)

Unmanned aerial systems (UAS), commonly known as drones, come in various sizes and shapes, each with capabilities and limitations. They can be broadly categorized into three types: Multirotor, Fixed-Wing, and VTOL (Vertical Take-off and Landing) (Suprapto et al., 2021). Multirotor drones are characterized by their use of multiple propellers and rotors for control. Typically equipped with four or more rotors, these drones can hover in place, making them well-suited for aerial photography, inspection, and search and rescue operations (Macias et al., 2022). Examples of multirotor drones include quadcopters and hexacopters. These UAS are highly manoeuvrable and can operate effectively in confined areas, both indoors and outdoors (Al-Obaidi et al., 2020).

On the other hand, Fixed-Wing drones have a design resembling a traditional aeroplane, featuring a single large wing and a tail. They generally offer incredible speed and extended range than multirotor drones, but they require a runway or a similar launch and recovery mechanism. Fixed-wing drones are commonly used for long-range reconnaissance, surveillance, and surveying.

VTOL (Vertical Take-off and Landing) drones combine the vertical take-off and landing capabilities of multirotor drones, like helicopters, with the ability to transition into horizontal flight, similar to aeroplanes. Combining the advantages of multirotor and fixed-wing designs, these drones are well-suited for applications such as search and rescue operations, surveillance, and mapping.

2.3 UAS Application for Road Accident Reconstruction in Forensic Investigation

Drones, also known as Unmanned Aircraft Systems (UAS), have become invaluable tools in forensic investigations for road accident reconstruction (Lyu et al., 2017). Equipped with high-resolution cameras and sensors, UAS captures detailed aerial imagery that offers a comprehensive view of the accident scene. This imagery allows for creating precise 2D and 3D models, facilitating accurate measurements, analysis of vehicle positions, and reconstruction of collision dynamics. UAS-photogrammetry helps identify and document crucial physical evidence, such as tire marks, debris patterns, and vehicle damage (Lyu et al., 2017).

One advantage of UAS is their ability to access challenging or hazardous terrains, enabling the efficient and safe surveying of remote or hard-to-reach locations (Horsman, 2016). They can capture real-time or near-real-time images and videos, ensuring non-disruptive scene documentation. Combining aerial imagery with photogrammetric techniques enables UAS to analyze velocity and trajectory, aiding investigators in determining vehicle speeds, evaluating paths, and identifying contributing factors such as skid marks and road conditions (Duma et al., 2022). UAS also assists in capturing witness viewpoints and testimonies through aerial interviews, providing valuable insights into the sequence of the accident.

Moreover, through advanced software analysis, the data collected by UAS supports sophisticated accident reconstruction simulations and virtual walkthroughs, enhancing the accuracy and reliability of the investigation process (Aleksandrowicz, 2020). Combining UAS and advanced software dramatically improves the ability to analyze and interpret the collected data, leading to more comprehensive and precise accident reconstructions.

2.4 Previous Study

In a study conducted by Mathew et al. (2022), the accuracy and effectiveness of Unmanned Aircraft System (UAS) Crash Scene Mapping, used by public safety agencies for crash scene documentation and mapping, are examined. The study utilizes mid-priced drones and a traditional ground-based real-time kinematic positioning base station. The method involves comparing measurements obtained from the ground-based base station with UAS-based photogrammetric mapping. The study evaluates the accuracy of UAS-derived and ground-control scale errors. The results indicate that UAS-derived scale errors were within 0.1 ft (3 cm) of field measurements, a commonly accepted public safety threshold. Most measurement errors, over 85%, were found to be within 0.1 ft (3 cm). Additionally, UAS-based mapping significantly reduces evidence documentation time, ensures the safety of first responders, and reduces incident clearance time.

Another study conducted by Almeshal et al. (2020) focuses on assessing the accuracy of a low-cost small unmanned aircraft system (sUAS) in reconstructing three-dimensional (3D) models of traffic accidents in Kuwait. The goal involves evaluating the accuracy of sUAS-based photogrammetry in reconstructing 3D models of traffic accidents. The study reconstructs 3D models of simulated accident scenes using a low-cost sUAS and a cloud-based photogrammetry platform. The accuracy of measurements is evaluated at different flight altitudes, and the impact of varying percentages of frontal and lateral overlaps on measurement accuracy is also investigated. The study finds that the sUAS-based photogrammetry method accurately reconstructs 3D models of traffic accidents, with root mean squared error (RMSE) ranging between 0.97 and 4.66 and mean percentage absolute error values. These findings provide insights into the reliability and applicability of UAS-based photogrammetry methods for traffic accident reconstruction.

3.0 Methodology

The methodology used in this study can be described as a systematic approach that aims to address the research problem by collecting data through a specific methodology and interpreting the gathered information. This section provides an overview of the overall approach and process employed in the study. Figure 1 depicts the process commences with a literature review and research planning phase, followed by data collection. The third phase involves data processing, and finally, the analysis is conducted in the fourth phase. Furthermore, this chapter offers a detailed description of the device and software utilized in the research.

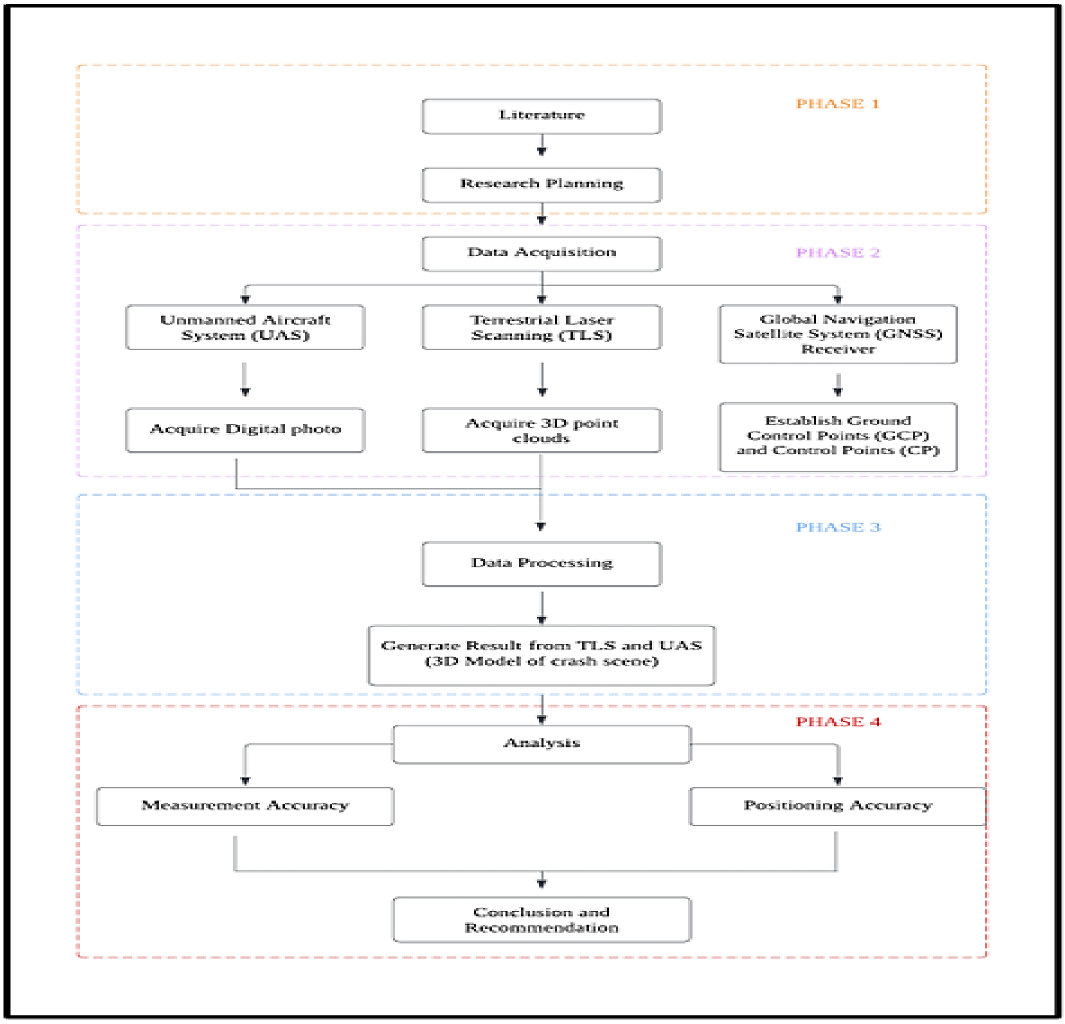

Figure 1. Research Methodology

3.1 Phase 1: Preliminary Study

This phase involves planning essential research tasks, which necessitates a comprehensive understanding of the literature review. This study adopts a comparative research methodology that combines qualitative and quantitative approaches. The planning process also encompasses setting up a simulated crash scene, acquiring the required data collection equipment, and the execution of the data gathering process. All of these aspects require careful planning to ensure successful data acquisition.

Subsequently, the research method was evaluated by implementing a simulated crime scene that closely resembled real crash scenes. The simulated crash scene occurred outdoors on the Universiti of Teknologi Malaysia (UTM) campus, as illustrated in Figure 2, depicting the arrangement of the crash scene setup. To collect the necessary data, a simulation of crash scenes was carried out at the designated location, specifically at Dataran Universiti of Teknologi Malaysia (UTM), located near Gate 3 in Skudai, Johor Bahru.

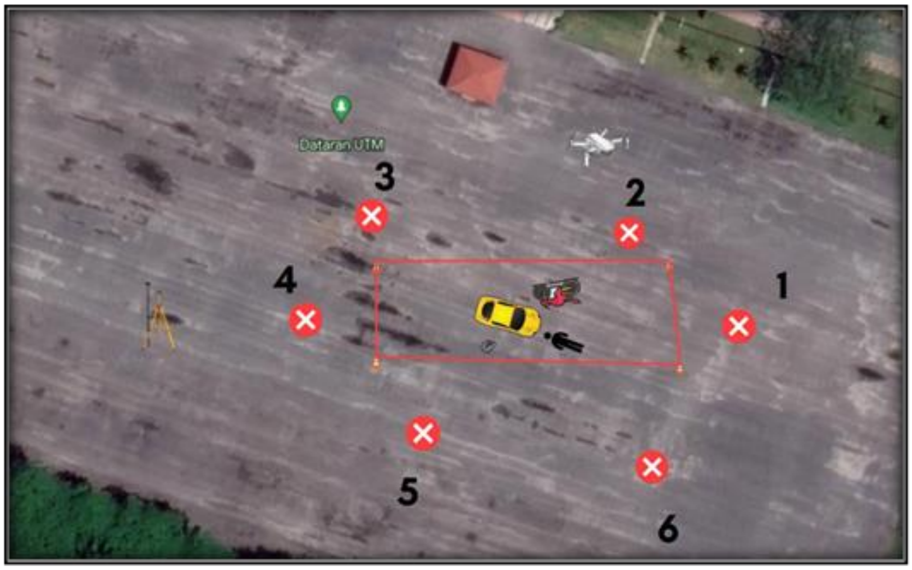

Figure 2. Crash scene setup and GCP placement

3.2 Phase 2: Data Acquisition

During Phase 2 of the study, data acquisition was carried out using a systematic methodology that involved the utilization of various technologies, namely Unmanned Aircraft System (UAS), Global Navigation Satellite System (GNSS) receiver, and Terrestrial Laser Scanning (TLS). The UAS was deployed at an altitude of 30 meters to capture high-resolution crash scene images, follow a predefined flight path, and generate a detailed 3D representation of the area. Concurrently, as portrayed in Figure 3, Terrestrial Laser Scanning (TLS) was utilized to create a 3D point cloud, serving as a reference for the UAS-based 3D reconstruction of the crash scene.

To ensure accurate spatial referencing, 6 Ground Control Points (GCP) and 7 Check Points (CP) were strategically positioned within the crash scene. These reference points were established by utilizing a GNSS receiver with the MyRTKnet technique, recording all coordinates in the World Geodetic System 1984 (WGS 84) coordinate system. The GCP coordinates played a vital role in georeferencing the acquired UAS images, aligning them with real-world coordinates to achieve spatial accuracy. Conversely, the CP coordinates served as benchmarks for evaluating the accuracy of the collected data. The accuracy and reliability of the data were assessed by comparing the known ground truth coordinates of the CP with their corresponding positions in the data images.

Figure 3. Data acquisition at the site

3.3 Phase 3: Data Processing

In Phase 3 of the study, the collected UAS data images were processed to generate a 3D model using the Structure from Motion (SfM) technique in Agisoft Metashape software. This versatile software performed various tasks, including photo alignment, georeferencing, dense point cloud generation, mesh creation, texture application, and exporting the final 3D model.

The UAS images were transferred to the data processing environment, where they underwent alignment and georeferencing processes to ensure accurate positioning. Through the

SfM technique, the software estimated camera positions and reconstructed the 3D structure of the crash scene. A dense point cloud was generated using the aligned and georeferenced photos, capturing a detailed representation of the crash scene. This point cloud served as the foundation for creating a mesh model that depicted the geometric structure of the scene.

To enhance visual realism, the original UAS images were projected onto the surface of the mesh model, applying texture mapping. This step added colour and details to the 3D model, making it more visually appealing and realistic. Finally, the completed 3D model was utilized for further analysis and interpretation, enabling researchers to extract valuable insights from the data.

However, Terrestrial Laser Scanning (TLS) data was processed using Leica Cyclone software to create a 3D representation of the crash scene. The process begins by capturing laser scans from various positions around the crash site using a Terrestrial Laser Scanner, followed by importing these scans into Cyclone software. Cyclone's robust registration tools ensure precise alignment of the scans, resulting in comprehensive scene coverage. The software offers advanced filtering and cleaning options to remove noise and outliers from the raw point cloud data, enhancing overall accuracy. Detailed analysis can be conducted on the point cloud, extracting measurements and dimensions critical to reconstructing the crash scene's geometry. Cyclone enables the generation of a complex mesh from the cleaned point cloud, forming the foundation for a lifelike 3D model. By integrating photographs taken at the scene, Cyclone allows the meshed surfaces to be textured, enhancing the model's realism. The processed data can be visualized within Cyclone's interface and in cloud compare software, facilitating virtual exploration of the crash scene from various angles for analysis, reconstruction, and even simulations.

4.0 Result and Discussion

This study assesses Unmanned Aircraft Systems (UAS) effectiveness in Forensic Mapping. It achieves this by scrutinizing the accuracy of measurements in both the Absolute and Relative contexts. UAS imagery was utilized using the Agisoft Metashape software to create a comprehensive 3D model of the crash scene. The researchers reconstructed the scene in three dimensions by capturing UAS images along specific flight paths. The resulting 3D model, as shown in Figure 4, comprising approximately 155 images, successfully captured the entirety of the simulated crash scene.

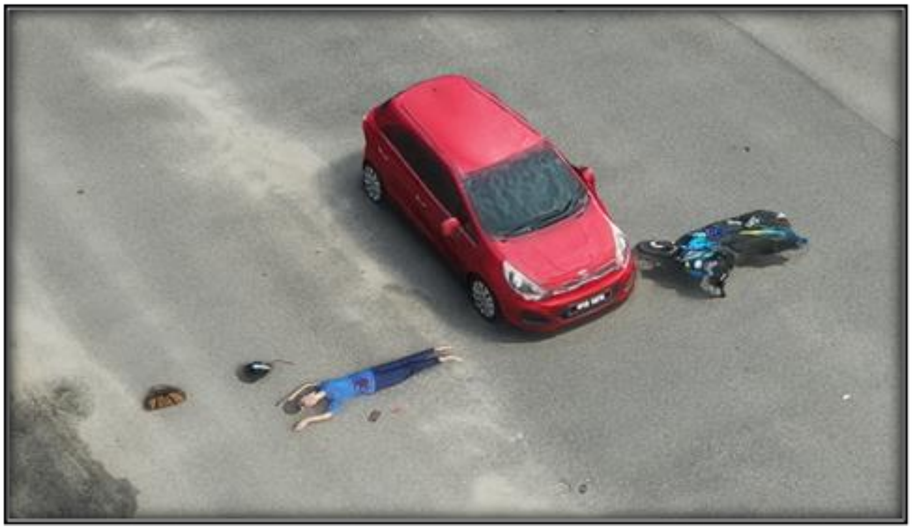

Figure 4. Complete 3D representation of a crash scene from UAS

A benchmark was established to assess the reconstructed 3D model's precision and dependability by utilizing a Terrestrial Laser Scanning (TLS) point cloud. The TLS data was obtained using a highly accurate laser scanner and processed using Cyclone software, renowned for its point cloud registration and analysis capabilities. The TLS point cloud served as a reference dataset for evaluating the model derived from the Unmanned Aircraft Systems (UAS), as shown in Figure 5. The TLS point cloud comprised 38,429,264 points, covering the entire extent of the crash scene.

Figure 5. Complete 3D representation of crash scene from TLS

For the analysis, measurements were executed on the objects of interest utilizing two separate software tools: Agisoft Metashape for processing data from Unmanned Aircraft Systems (UAS) and Cloud Compare for processing data from Terrestrial Laser Scanning (TLS), as illustrated in Figure 6. The TLS data served as a reference point for comparing the measurements obtained from the UAS. The primary focus of the measurements was to ascertain the relative accuracy of UAS data for applications in forensic investigation, particularly in measuring object lengths. The aim was to assess the alignment between UAS and exceptionally accurate TLS measurements.

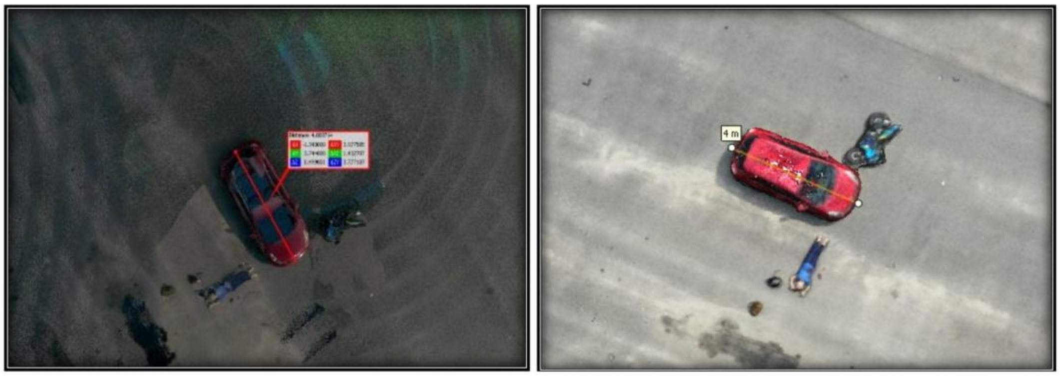

Figure 6. Crash scene model – distance measurement analysis. Measurements done for TLS (left) and UAS (right)

The Root Mean Square Error (RMSE) method assessed the measurements’ accuracy. RMSE is a statistical technique that quantitatively evaluates the differences between the measurements obtained from the Unmanned Aircraft Systems (UAS) and the Terrestrial Laser Scanning (TLS). It measures the accuracy and potential discrepancies between the two datasets. By comparing the UAS measurements with the TLS measurements and using RMSE as the evaluation metric, it is possible to determine the relative accuracy of the UAS data for forensic investigation purposes (see equation 1). This analysis offers valuable insights into the level of precision and reliability that can be attained with UAS measurements, particularly in capturing the lengths of objects.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(yi - \hat{y}i)^2}{N}} \qquad \text{(Equation 1)}$$

Where,

yi : true value

$\hat{y}i$: observed value

N : number of observations

As depicted in Table 1, the analysis results were obtained using the Root Mean Square Error (RMSE) calculation. This measurement error highlights the differences between the benchmark measurements derived from the Unmanned Aircraft System (UAS) and the TLS system. The RMSE value for both TLS and UAS was found to be ±4.1 cm. In statistical terms, a lower RMSE value indicates a more accurate model. Additionally, the accompanying figure presents a visual chart featuring ten samples from the dataset, displaying the RMSE values of the UAS relative to the TLS benchmark.

Table 1. Error of measurement

Relative		
No.	Items	Error measurement (cm)
		UAS-TLS
1	Car	1
2	Bike	-0.6
3	Bag	0.5
4	Mannequin	1
5	Wallet	-0.2
6	Phone	4
7	Cone 2-3	6
8	Cone 1-2	7
9	Cone 3-4	5
10	Cone 1-3	6
RMSE		4.1

The graph presented in Figure 7 shows that the differences in measurements between the Unmanned Aircraft System (UAS) and Terrestrial Laser Scanning (TLS) are relatively minimal. However, in the case of measurement number 8, which involves the distance between cone 1 and cone 2, it is evident that the UAS exhibits a significantly higher error of ±7 cm. This noticeable discrepancy may be attributed to factors such as distortion in the captured images or inadequate image overlap during the data acquisition. Considering the TLS data as the benchmark, the UAS is sufficient and meets the desired standards for the intended purpose, with an error margin of ±4.1 cm.

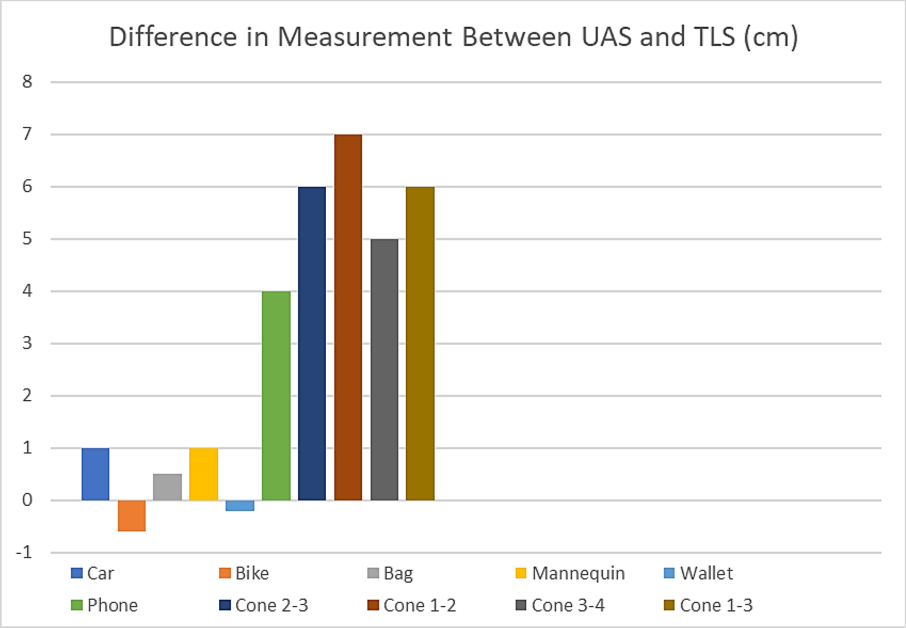

Figure 7. Difference in measurement between UAS and TLS data in meter (m)

This study selected seven points as checkpoints to assess the accuracy of the UAS image processing. The reliability of the dataset was evaluated by calculating the root mean square error (RMSE) between the coordinates of these points on the generated 3D model and the coordinates obtained from the GNSS receiver. A lower RMSE value indicates higher accuracy. The values of RMSE are provided in Table 2. The resulting RMSE values were ±0.20719 for the X coordinate, ±0.164 for the Y coordinate, and ±0.001584 for the Z coordinate. These RMSE values indicate the average magnitude of the differences between the two sets of coordinates, demonstrating the accuracy and precision achieved in the data alignment process. The relatively small RMSE values for X, Y, and Z suggest that the dataset is reliable, and the generated 3D model aligns closely with the coordinates obtained from the GNSS receiver, validating the accuracy of the dataset for the project’s intended purposes. The analysis revealed that the residuals’ root mean square error

(RMSE) was less than 1 meter, indicating a high level of accuracy in the measurements. A lower RMSE value correlates with higher accuracy, affirming the reliability and precision of the dataset.

Table 2. RMSE for UAS data

Absolute									
Check	Coordinates from UAS			Coordinates from GPS			Differences		
Points	X	Y	Z	X	Y	Z	ΔX	ΔY	ΔZ
CP 1	349121.27	171600.93	17.2751087	349121.5	171600.8	17.273	-0.255	0.143	0.0021087
CP 2	349124.28	171609.22	17.3085063	349124.2	171609.1	17.306	0.031	0.101	0.0025063
CP 3	349117.72	171610.78	17.3144095	349118.1	171611.1	17.314	-0.359	-0.314	0.0004095
CP 4	349113.71	171609.12	17.2978671	349113.8	171609	17.299	-0.137	0.085	-0.001133
CP 5	349130.62	171602.92	17.2635677	349130.8	171602.7	17.262	-0.22	0.197	0.0015677
CP 6	349128.4	171603.36	17.2806095	349128.4	171603.4	17.279	-0.021	0.002	0.0016095
CP 7	349128.29	171608.78	17.2875757	349128.5	171608.9	17.287	-0.195	-0.114	0.0005757
						RMSE	± 0.20719	± 0.164	± 0.001584

5.0 Conclusion

The study yielded remarkable insights into the accuracy achieved by both TLS and UAS, with a relative accuracy RMSE value of ±4.1 cm. In statistical terms, a lower RMSE value signifies a more precise model. The absolute accuracy results unveiled RMSE values of ±0.20719 for the X coordinate, ±0.164 for the Y coordinate, and ±0.001584 for the Z coordinate. The primary objective of this investigation was to evaluate the accuracy and precision of Unmanned Aircraft Systems (UAS) in the realm of forensic mapping, especially their capacity to capture crucial evidence while upholding the integrity of crash scenes through the creation of 3D models.

The study fulfilled its goals by harnessing UAS and processing the acquired data through Agisoft Metashape software. Using Root Mean Squared Error (RMSE) for analysis demonstrated that the UAS exhibited absolute and relative accuracies within acceptable margins. This research effectively showcased the competence of UAS in forensic mapping, underscoring its appropriateness for forensic applications and its aptitude in attaining the requisite level of precision.

The outcomes of this inquiry bear substantial advantages for professionals engaged in forensic investigations, particularly in crash scene analysis. Leveraging UAS in tandem with sophisticated processing software enhances data capture efficiency, preserves scene integrity, and facilitates the creation of precise 3D models. UAS offers the benefits of remote accessibility, cost-effectiveness, and heightened safety by enabling access to challenge terrains and minimizing potential risks for investigators. Overall, this study equips practitioners with an efficient toolkit for evidence collection, thorough analysis, and meticulous scene preservation, bolstering the quest for justice and streamlining case resolution.

Several recommendations are proposed to improve the realism and accuracy of crash scene reconstructions using UAS. Firstly, selecting locations that combine man-made structures and natural surroundings enhances the authenticity of the crash scene simulation, making it more representative of real-life scenarios. Secondly, flying UAS at lower altitudes allows for capturing finer details. Thirdly, increasing the number of Ground Control Points (GCPs) enhances the model's accuracy. Lastly, incorporating blood splatter in the reconstruction process aids forensic analysis. By implementing these recommendations, forensic investigators can create more realistic and accurate crash scene reconstructions, facilitating detailed analysis and interpretation.

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