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Toward 3D reconstruction of damaged vehicles for investigating traffic accidents in Thailand using a photogrammetric approach

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Abstract

Traffic accident investigation by the police forensic science department in Thailand is essential to determine their causes. The collection of forensic evidence from damaged vehicles after an accident plays a significant role in damage assessment and collision trajectory analysis. This study employs a photogrammetric approach using an off-the-shelf mobile device and free software for the three-dimensional (3D) reconstruction of damaged vehicles to investigate traffic accidents. In this study, the iPhone XS Max mobile phone camera was used for image acquisition of close-range photogrammetry and videogrammetry. After image capture, 3D models of forensic evidence were automatically reconstructed from the imagery using the COLMAP open-source software that provides user-friendliness to non-experts. The 3D models of the deformed vehicles were later used to analyze the damage and collision trajectory of a traffic accident. The results showed that for accuracy assessment of the 3D model test car, the values of root mean square error (RMSE) obtained from still images, video, and video with a stabilizer were 2.5, 3.1, and 2.4 cm, respectively. The completeness of the generated 3D model obtained from still images provided greater clarity than videos with and without stabilizers, respectively. Therefore, the photogrammetric approach using a mobile device played a significant role in the 3D reconstruction of the forensic evidence used for traffic accident investigations, providing essential 3D information for court trial reports.

Keywords: Forensic science, Traffic accident investigation, 3D Reconstruction, Close-range photogrammetry, Videogrammetry

1. Introduction

Forensic science uses intelligence (science-based philosophies) to obtain and process evidence to pursue a criminal case [1]. Forensic police are typically responsible for inspecting a crime scene and providing evidence used for scientific analysis. Methods used include evidence collection, witness comparison statements, and photographic documentation to aid investigators, inquiry officials, and judicial agencies in searching for proof of scientific truth [2]. Traffic accidents are common in Thailand, and road traffic deaths have remained steadily unchanged in the last decade [3]. The majority of forensic police tasks are the investigation of vehicle accidents. However, traffic accident data cannot be accurately verified for impending investigation because the information collected is not immediately recorded after the incident. Damaged vehicles are typically stored at a police station, where they await inspection for evidence. Forensic police are currently responsible for collecting forensic evidence and documenting scratches and other damage to each vehicle using traditional methods, including digital photographs and measurements using tape measures [4]. The outcomes of these investigations are essential to verify a collision while also analyzing the traffic accident collision trajectory so that the documentation can be utilized during a court trial.

Nonetheless, the traditional forensic police approach can result in inadequate evidence collection, which may cause a lack of precision in the measurement methods. Conventional forensic image evidence-gathering methods are based on two-dimensional techniques, whereas 3D image measurements have not been used as widely. Moreover, it might be challenging to analyze and prove collision trajectories in cases where large vehicles are involved, and the accident investigation time might increase. Over the last ten years, geomatics technologies have begun to be employed in forensic applications using tools and methods such as a Total station surveying [5, 6], Terrestrial laser scanning (TLS) [7, 8], and photogrammetry [2, 9]. The use of a Total station and TLS are more expensive than the photogrammetry approach, which is an important consideration given the budgetary constraints placed on forensic police, making the photogrammetry approach the most practical and cost-effective option. Photogrammetry has been used extensively to acquire spatial data or three-dimensional (3D) models for various forensic applications. Examples include the creation of 3D models of deformed vehicles after an accident [10, 11], recording traffic accident scenes [4, 12, 13], documenting crime scenes [14, 15], collecting physical forensic evidence [15], analyzing forensic pathology [16], and verifying person identification [17]. The use of 3D modeling to aid forensic police in reconstructing traffic accidents for forensic investigation is the focus of this study.

The overall purpose of this study is to demonstrate the potential of a photogrammetric approach using a mobile phone's digital camera and free/open-source software for forensic police investigation of vehicles damaged in traffic accidents. The study is based on

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3D reconstruction from imagery using close-range photogrammetry and videogrammetry to deliver 3D models of damaged vehicles. Effective damaged vehicle 3D modeling was achieved in this research by employing image acquisition methods (i.e., taking photos for 3D vehicle modeling and recording video with mobile phone stabilizer) and additional techniques before photogrammetric processing (i.e., camera calibration and blurred image detection). The quality assessment in terms of position accuracy and completeness of the reconstructed 3D model of a test vehicle using the photogrammetric approach is presented to ensure the accuracy of vehicle damage measurements after an accident. Furthermore, to demonstrate the potential of such an approach, the investigation of a real traffic accident was utilized to determine the reliability of the results under actual conditions in assessing the damage to each vehicle and analyzing collision trajectory after the accident.

The remainder of this paper is organized as follows. Section 2 describes the experimental design of this study and the photogrammetric workflow for traffic accident investigation. In Section 3, the potential use of smartphone cameras for 3D reconstruction of a test car is presented, including camera calibration, data acquisition methods, blurred image detection pre-processing, photogrammetric processing, and the comparison of results from different photogrammetric approaches. Section 4 applies a photogrammetric approach to an actual traffic accident investigation. Section 5 discusses the outcomes of the proposed methods, compared to traditional techniques, and the limitations of these methods. Finally, Section 6 summarizes the conclusion and discusses the next steps to improve the photogrammetric results in future work.

2. Experimental design

There are increasing numbers of affordable mobile devices, tablets, and smartphones available on the market. These mobile devices employ high-resolution digital cameras with enormous potential for low-cost image acquisition for photogrammetry in various applications. In particular, smartphones (or mobile phones) have been extensively used for photogrammetric approaches in forensic science applications, such as on-site traffic accident investigation [13], crime scene recordings [18], and forensic pathology education [19]. This study focuses on using an off-the-shelf mobile phone for photogrammetric image acquisition due to its convenience and affordability. Table 1 shows the technical details of the iPhone XS Max mobile phone camera used in this study.

Table 1 Technical specifications of the iPhone XS Max camera

Characteristics	iPhone XS Max
Processer	A12 Bionic chip
Image format	4,032 x 3,024 (12MP)
Video format	3,840 x 2,160 (8MP)
Sensor size	5.6 x 4.2 mm
Pixel size	1.4 µm
Lens maximum aperture	Wide-angle: $f/1.8$
	Telephoto: $f/2.4$

For photogrammetric application in traffic accident investigation, the methodology in this study was carried out as illustrated in Figure 1. There are two main parts, as follows: (i) evaluating the image acquisition methods and results of a photogrammetric approach for 3D modeling of a test car; (ii) using reconstructed 3D models from damaged vehicles to investigate an actual traffic accident. In terms of image acquisition methods used, there were three main approaches based on close-range photogrammetry and videogrammetry: (i) still images; (ii) video; and (iii) video with a mobile phone stabilizer. For videogrammetry, video recordings decreased the data collection time, overcoming time constraints to avoid forensic evidence contamination [20]. A mobile phone stabilizer was utilized to control the quality of video recordings [21]. For both close-range photogrammetry and videogrammetry, camera calibrations from still images, video, and video with a mobile phone stabilizer were required before image acquisition to obtain essential parameters used in photogrammetric processing for each approach. Next, imagery and videos were collected from around a test car, and blurred image detection was used to control image quality before processing.

For photogrammetric processing based on computer vision, the Structure-from-Motion (SfM) and multi-view stereo (MVS) techniques have widely utilized for 3D reconstruction form the imagery, such as point cloud or 3D mesh [22]. The COLMAP, a free software based on SfM and MVS techniques, was used for photogrammetric processing to generate the point clouds of a 3D vehicle model in this study. Afterward, the post-processing of de-noising was used to eliminate 3D point cloud outliers to improve the photogrammetric results. However, these point clouds did not have any spatial information, so a registration process was required to obtain the actual 3D model size. However, these point clouds did not have any spatial information, so a registration process was required to obtain the actual 3D model size. For registration, there were two approaches: 1) scaling the 3D model with scale bars, and 2) using target observation with a total station survey. The next step evaluated the performance of the image acquisition methods and the quality of photogrammetric results for 3D reconstruction of a test car, including both the positional accuracy and 3D model completeness. Finally, a comparison of distances and locations of independent checkpoints (ICPs) between the 3D model and total station survey data was used to calculate errors for accuracy assessment.

Two vehicle 3D models for forensic evidence were reconstructed from damaged vehicle imagery following the aforementioned photogrammetric workflow for an actual traffic accident investigation. Each vehicle's 3D model was inspected to identify the scratches and other damage from the collision. The collision trajectory analysis was based on an accident reconstruction technique using a 3D simulation for both deformed vehicles. Finally, the proposed technique results for the virtual traffic accident scene were compared to traditional forensic police methods to provide a preliminary assessment of photogrammetric approach capabilities.

3. Potential use of smartphone camera for test car 3D reconstruction

To compare different image acquisition approaches for close-range photogrammetry and video captured for videogrammetry, the reconstruction of a 3D model for a test car was studied in this research. The model was derived from three photosets using still images, videos, and videos with stabilizers from an off-the-shelf mobile phone camera for this experiment.

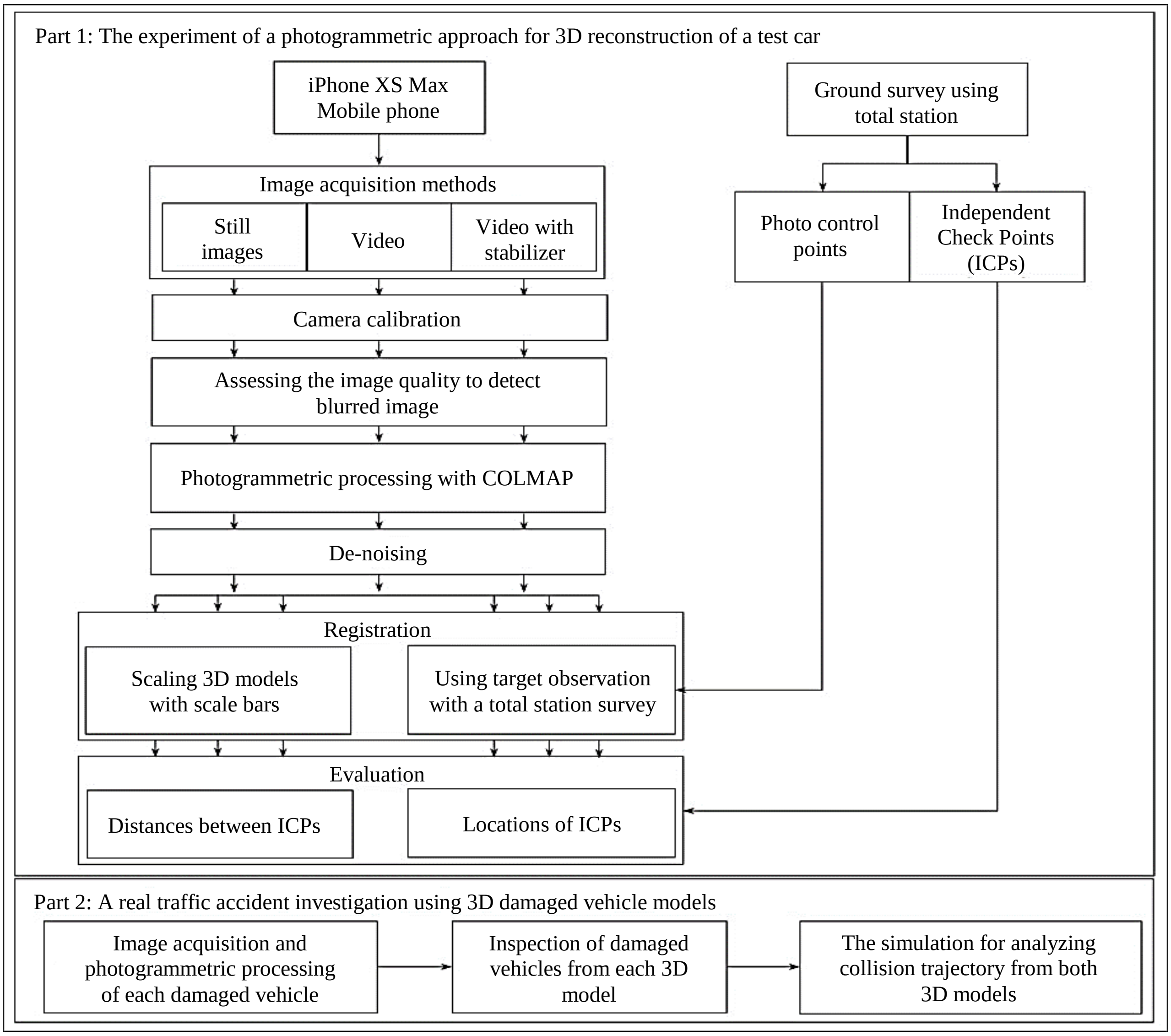


Figure 1 Methodology scheme used in this study

3.1 Camera calibration

Typically, a non-metric digital mobile phone camera is not used for photogrammetric purposes. High-precision photogrammetric measurements require camera calibration features to examine geometric images and camera properties, such as focal length identification (f), image coordinates of the principal point (Xp, Yp), radial lens distortion (k1, k2, k3), and tangential distortion (p1, p2). Automatic calibration, based on computer vision techniques, is widely used for non-experts because of the convenience of a fully-automated calibration processing system [23]. In this research, an iPhone XS Max camera captured different view angles around a chessboard. Twelve still images and videos were taken for calibration of the template. Videos were also recorded using the same camera with a DJI Osmo Mobile 3 monopod mobile phone stabilizer. Afterward, both videos were extracted to acquire the image datasets for camera calibration. Finally, automatic calibration was processed using Python script language coding, including the OpenCV library. The calibration results for each determined parameter of the iPhone XS Max camera are shown in Table 2.

Table 2 Camera calibration results from three data acquisition approaches

Parameter	OpenCV		
	Still images	**Video**	**Video with stabilizer**
f-focal length (pixel)	3084.008	3055.462	3057.433
Xp-principal point X (pixel)	2019.549	1831.469	1921.237
Yp-principal point Y (pixel)	1474.665	1021.232	1027.831
k1-radial lens distortion 1	2.67E-01	2.50E-01	2.84E-01
k2-radial lens distortion 2	-1.38E+00	-1.17E+00	-1.54E+00
k3-radial lens distortion 3	2.33E+00	1.75E+00	2.64E+00
p1-tangential distortion 1	-2.28E-03	-2.22E-03	-2.63E-03
p2-tangential distortion 2	6.28E-05	-1.13E-02	-1.66E-03

The camera calibration results in Table 2 show that the calibration parameters are slightly different for each method. However, the values of each parameter obtained from these approaches were applied to establish the initial parameters for photogrammetric processing camera models [4]. The problem of images extracted from the videos was especially challenging because, unlike still images, the absence of an exchangeable image file (Exif) data format did not allow initial camera model parameters to be adopted. The use of still images for close-range photogrammetry does not suffer from this problem because an image's Exif metadata can provide the main camera model parameters used in the photogrammetric processing stage. Inadequate camera model parameters for processing may lead to errors in photogrammetric results [24]. Therefore, camera calibration was essential to provide enough parameter data for both videos obtained in the photogrammetric processing.

3.2 Data acquisition

In this experimental study, a 2003 Toyota sedan was used as the test car, and the photogrammetric approach was used for the 3D reconstruction. Before image acquisition, the placement of control points was required to denote the points for the 3D model. Other checkpoints were used to evaluate the accuracy of the 3D model reconstruction. Targets for six control points and twenty-five checkpoints were attached to the vehicle, as shown in Figure 2(a). The location of these target points was determined by a total station survey using the intersection method (Figure 2(b)). Image acquisition of the vehicle was accomplished at different levels with sufficient overlapping to provide an effective photogrammetric reconstruction. Figure 2(c) shows a photographer facing perpendicular to the vehicle at a distance of 1 to 2 meters, while the cameras are stationed approximately 1 meter away. Each image acquisition approach was derived from three separate 360-degree rotations around the vehicle at different camera levels: 1) above the head, 2) at the chest, and 3) at the photographer's knee. Videos with and without a stabilizer were extracted every second to prepare image datasets for videogramerty, as shown in Table 3.

(a) (b) (c)

Figure 2 Data collection in this study: (a) targets established as control points and checkpoints; (b) total station survey for target locations; (c) example of image acquisition

Table 3 Comparison of image acquisition for each method

Method of image acquisition	Data acquisition time (min)	Number of images
Still images	11.07	131
Video	2.19	150
Video with stabilizer	2.36	151

3.3 Pre-processing for assessing the image quality to detect blurred images

Image quality plays an important role in the accuracy of photogrammetric measurements because it is a factor that has a direct effect on the quality of 3D model reconstruction [22, 25]. The use of blurred images in photogrammetry might lead to a low-precision measurement on the image, resulting in low accuracy in the 3D model results [26]. To deal with such image quality problems, especially blurred images extracted from the video due to reduction errors in photogrammetric measurements, the image quality assessment from analyzing edges was carried out with the OpenCV library in the Python script using the Laplacian function. An image with very low Laplacian values was assumed to be blurred. However, the researcher manually selected and removed blurred images, which were not processed for photogrammetry. The results from analyzing the image quality using the Laplacian function are shown in Figure 3.

Based on Figure 3, the distribution of Laplacian values from the video was lower than the video with a stabilizer or the still images, respectively. These results show that the images derived from the video with a stabilizer can help control image acquisition quality, reducing the number of blurred images. However, the distribution of Laplacian values from the still images was noticeably higher than both video sources.

3.4 Photogrammetric processing and results

Photogrammetric processing using the COLMAP software employs semi-automated workflow for 3D model reconstruction and the initial camera model parameters obtained from the previously discussed camera calibration were used in this processing. The photogrammetric results from the COLMAP software were in the form of a 3D point cloud without any spatial information. Each 3D point cloud was manually registered by identifying the six targets as control points or scaling with scale bars using the CloudCompare software to provide a nearly actual vehicle size. Also, de-noising was carried out manually using the CloudCompare software to remove outliers in the point cloud. Visual comparison and details of the results provided by different image acquisition methods are shown in Table 4 and Figure 4.

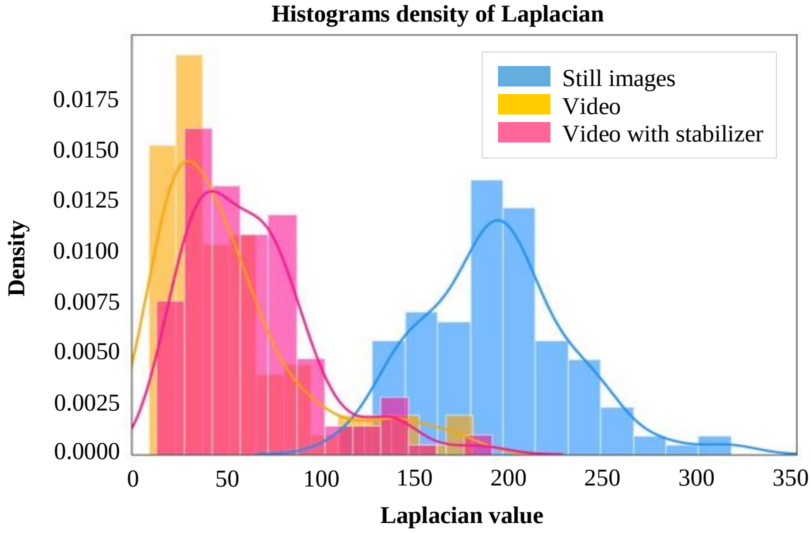


Figure 3 The distribution of Laplacian values between still images, video, and video with stabilizer obtained from image quality assessment using python script with OpenCV library

Table 4 Comparison of photogrammetric results from each image acquisition method

Method of image acquisition	Number of blurred images	Number of images used in processing	Number of points	RMSE of transformation after registration (m)
Still images	0	131	4,523,587	0.007
Video	8	142	1,599,988	0.029
Video with stabilizer	9	142	3,411,679	0.008

(a) (b) (c)

Figure 4 Point clouds obtained from the three image acquisition approaches: (a) still images, (b) video, (c) video with stabilizer

In comparing the 3D point cloud results from each model, it can be seen that the number of points in Table 4 and the completeness of the 3D models obtained from the still images were greater than a video with stabilizer and video, respectively. Because of image acquisition quality from the experimental results in section 3.3, higher image quality leads to better image matching. As a result, a larger number of points was generated. In particular, the 3D point cloud of the video (without stabilizer) had the highest number of outliers (Figure 4(b)) and the highest RMSE of transformation after registration (Table 4). However, the overall 3D point cloud results showed a data void in the same areas of each model, such as the roof, hood, and doors. Due to the limitations in the dense reconstruction of the image, imperfect texture characteristics or inadequate details required to generate the point clouds cannot be established.

3.5 Accuracy assessment of 3D models

The quality of results obtained from the photogrammetric technique in this experiment was ensured by assigning 25 targets points as independent checkpoints (ICPs) on the vehicle and were used as accuracy assessment points for the 3D models for each approach. The identification of the 25 ICPs in each point cloud was carried out using the CloudCompare software and was compared to the location of ICPs using the total station survey. In accuracy assessment of the photogrammetric results for scaling with scale bars, 25 distances between pairs of ICPs were measured from the point cloud using the CloudCompare software and compared to distances between ICPs from the total station survey data. The evaluation of the photogrammetric results is given in Table 5.

Based on the presented results of Table 5, the values of almost all statistic parameters (i.e. mean, standard deviation (SD) and RMSE) in all-dimensional errors from video approach were highest; whereas, the still image and video with stabilizer were lower than the video indicating that image acquisition from video yields the most inferior photogrammetric result quality. The RMSE of approach from video, still image, and video with stabilizer were 0.031, 0.025 and 0.024 m, respectively. Furthermore, the statistical errors from different registration methods of scaling with scale bars and using target observation with a Total station survey were slightly different (at the centimeter level). The strength of such an approach is that using scale bars to scale damaged vehicle 3D models is more convenient and requires less equipment usage by the forensic police. Thus, the photogrammetric technique using a mobile phone camera in this experiment is deemed capable of providing 3D model results to an accuracy of 2-3 centimeters for investigating damaged vehicles.

Table 5 Comparison of statistical errors for distances and locations from 25 ICPs based on a photogrammetric approach with a total station surveying

Registration method	Dimension	Method	Errors				
			Min (m)	Max (m)	Mean (m)	SD (m)	RMSE (m)
Scaling with scale bars	Distances	Still images	-0.016	0.003	-0.007	0.005	0.008
		Video	-0.032	0.032	-0.003	0.014	0.014
		Video with stabilizer	-0.019	0.006	-0.007	0.006	0.009
Using target observation with a total station surveying	X	Still images	-0.013	0.073	0.006	0.016	0.017
		Video	-0.017	0.032	0.003	0.014	0.014
		Video with stabilizer	-0.009	0.077	0.003	0.016	0.016
	Y	Still images	-0.008	0.096	0.003	0.019	0.018
		Video	-0.040	0.051	0.008	0.026	0.026
		Video with stabilizer	-0.011	0.092	0.003	0.018	0.018
	Z	Still images	-0.007	0.015	0.001	0.004	0.004
		Video	-0.022	0.012	0.001	0.008	0.008
		Video with stabilizer	-0.009	0.009	-0.001	0.004	0.004
	All	Still images	-0.013	0.096	0.003	0.014	0.025
		Video	-0.040	0.051	0.004	0.017	0.031
		Video with stabilizer	-0.011	0.092	0.002	0.014	0.024

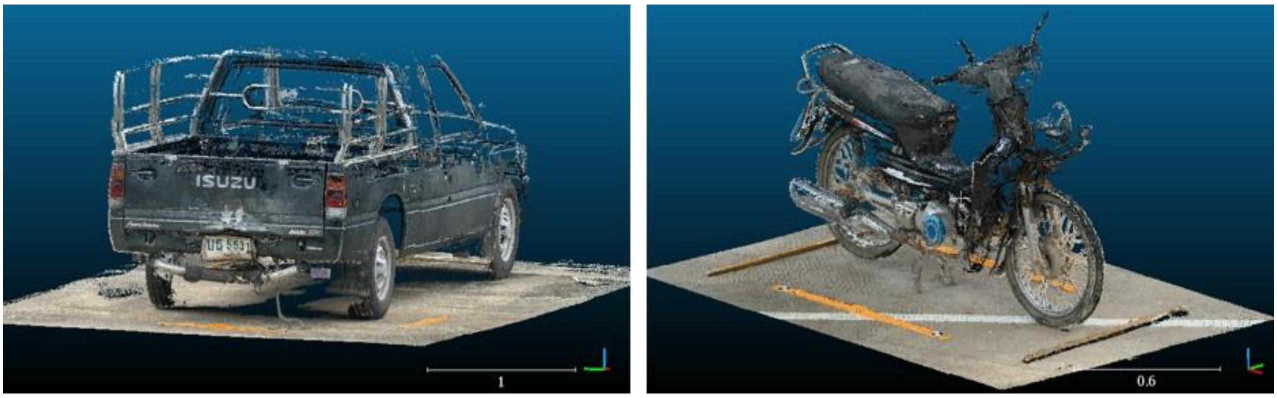
4. Actual traffic accident investigation from 3D models of damaged vehicles

This case study employs the photogrammetric approach for practical forensic application to a traffic accident investigation compared to the traditional forensic science methods used by the police in Thailand. The 3D model reconstruction of damaged vehicles utilizes an off-the-shelf mobile phone camera for image acquisition and free software for automatic photogrammetric processing. The 3D models of the damaged vehicles were evaluated to identify potential traffic accident investigation issues, such as the measurement of damaged areas or proving the collision trajectory based on the currently used but antiquated accident reconstruction technique. The outcomes of this technique are presented by compiling the analyzed results into 3D documentation for facilitating traffic accident investigation.

4.1 Experimental study

The case used in this experimental study involved an actual collision between a pickup truck and a motorcycle on 8th September 2020. A preliminary investigation indicated that the motorcycle crashed into the rear of the pickup truck while it was parked on the side of the road. The photogrammetric approach for 3D model reconstruction using an iPhone XS Max camera acquired images of the damage to both vehicles. However, only the still images were used for this experimental investigation case because they could provide high-quality photogrammetric results. Moreover, direct contact by the investigators is not allowed because the placement of target markers on the body of a vehicle could potentially contaminate the accident evidence. The placement of two scaled bars near the vehicles synchronized the sizing of the damaged vehicle 3D models to the actual pickup truck and motorcycle to overcome this problem.

This study used two datasets of the combined pickup truck and the motorcycle imagery for data preparation and processing, consisting of 109 and 78 images, respectively. Initially, the photogrammetric process was carried out using the COLMAP software to generate point cloud data of each vehicle. Subsequently, 3D point cloud de-noising for both vehicles was performed manually to eliminate outliers using the CloudCompare software. Finally, the scaling of each vehicle model was carried out by identifying the four targets located in the two- point cloud scale bars found in the CloudCompare software. The resulting 3D models obtained from the above methods of both the pickup truck and motorcycle are illustrated in Figure 5.

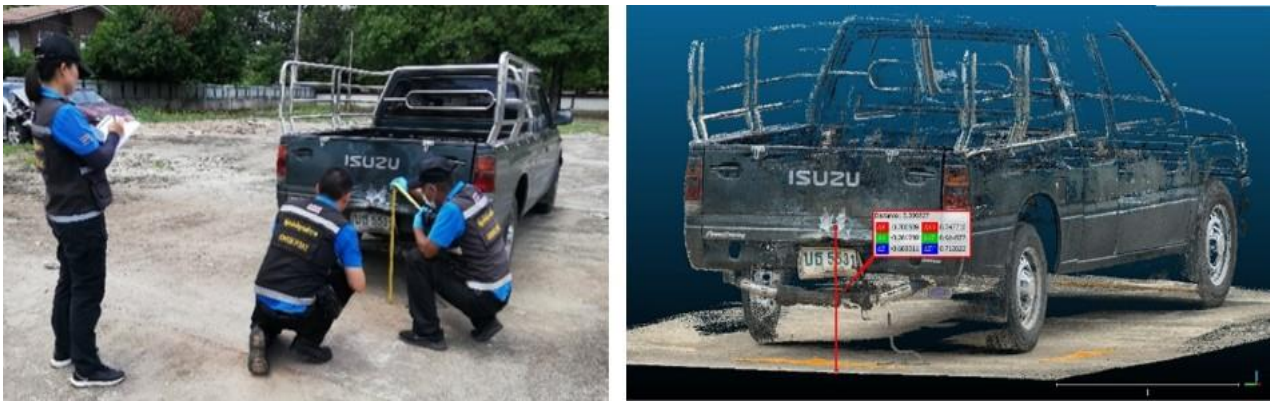


(a) (b)

Figure 5 3D Point cloud of both damaged vehicles: (a) pickup truck, (b) motorcycle

4.2 Inspection of damaged vehicle from 3D model

The traditional method of police forensic science for damaged vehicle inspection begins with observing the vehicle damage. The positions and amounts of damage to each vehicle from the collision are then determined using a tape measure. During the inspection of the damaged vehicles, these details are documented, and images are attained with a digital camera. This process follows the requirements for traffic accident investigation, as shown in Figure 6(a). Meanwhile, the application of 3D vehicle models is utilized to provide an alternative inspection of the damaged vehicles. The advantages of the proposed technique are the ability to perform additional inspections of the damaged vehicles later and with greater convenience (i.e., avoiding contamination of the forensic evidence, decreased collection and inspection time) compared to the traditional forensic police methods. The collision damage assessment for each vehicle was performed by distance measurement in the 3D point cloud using the CloudCompare software (Figure 6(b)).



(a) (b)

Figure 6 Inspection methods of damaged vehicle: (a) traditional forensic police method; (b) measuring distance on 3D model using the CloudCompare software

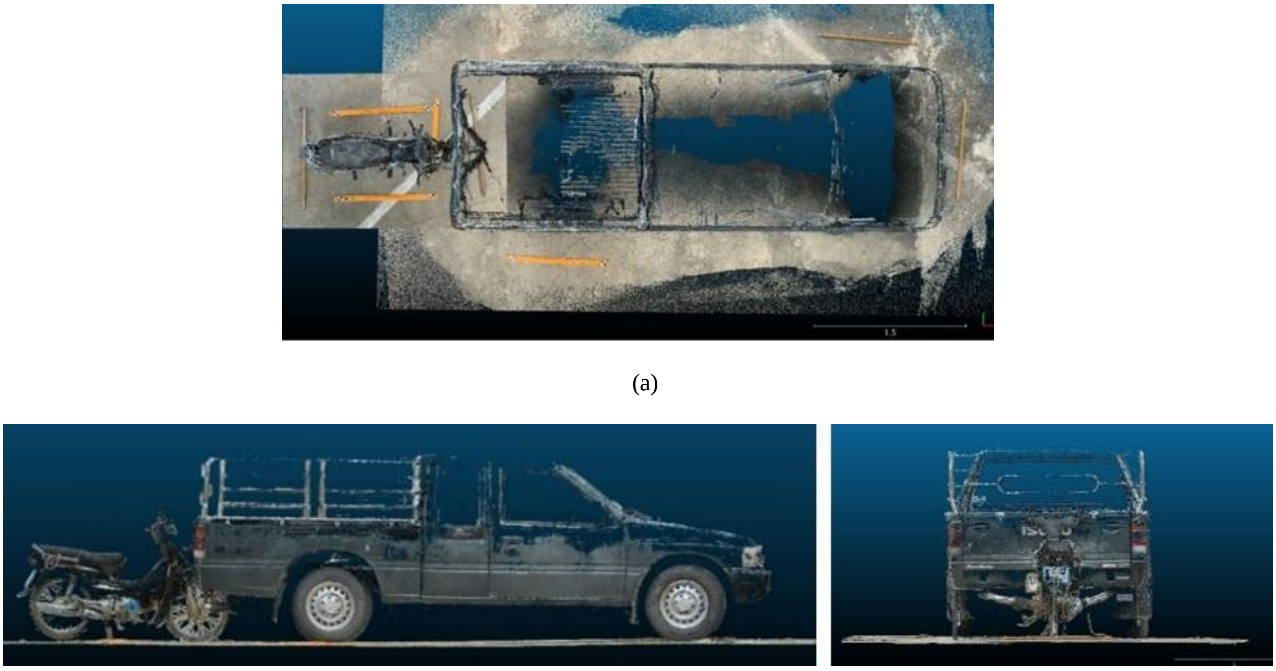
Assessing the damage inspection process using a 3D model as proposed in this study, the 3D point cloud approach can help to identify and measure damage to the vehicle. The 3D point cloud data is sufficient to reveal the vehicle damage patterns while providing better evidence visualization in an accident environment than the evidence in the original imagery. However, the details of the 3D point cloud obtained from the photogrammetric method may have missing data, depending on the size of the damage, which may produce incomplete visuals that result in inaccurate evidence documentation.

4.3 The simulation for analyzing collision trajectory

The purpose of traffic accident investigation of damaged vehicles for forensic evidence is to determine two aspects: 1) providing proof of the collision of the vehicles, and 2) analyzing the collision trajectory to be documented for a trial proceeding. Normally, forensic police officers compare the damage from each vehicle, and then both damaged vehicles are positioned to simulate the moment of the collision. This traditional approach for analyzing collision trajectory in the field might be challenging for larger vehicles (i.e., trucks). On the other hand, 3D models of damaged vehicles obtained from the photogrammetric approach can potentially overcome this constraint through a 3D reconstruction simulation of the collision trajectory (Figure 7). Figure 8 shows an example of the collision trajectory analysis generated in the 3D simulation by rotation of the model until alignment and 3D translation of the damaged vehicle models are achieved using the CloudCompare software. Additionally, this simulation produces 3D documentation that can be adopted for diverse traffic accident scenes to provide higher precision accident investigation.

(a) (b)

Figure 7 Comparison of the simulation for analyzing collision trajectory: (a) traditional forensic police method; (b) alignment of 3D models using the CloudCompare software



(a)

(b) (c)

Figure 8 The 3D documentation of a traffic accident investigation: (a) top view, (b) front view, and (c) right-side view of the simulation for analyzing collision trajectory

5. Discussion

This research aims to effectively assist in investigating accident reconstruction by employing a 3D model as forensic evidence. The application of this photogrammetric technique, which is extracted from the imagery of damaged vehicles, will provide forensic police with the tools needed to investigate traffic accidents and analyze collision trajectories. At the same time, these techniques will deliver more accurate documentation and simulation of the accident. The findings of this study clearly demonstrate the potential of an off-the-shelf mobile phone digital camera coupled with the use of free/open-source software packages to generate 3D models to provide evidentiary information for forensic investigations. The accuracy of these photogrammetric methods is enhanced with additional techniques, including camera calibration, blurred image detection, and de-noising. The 3D model reconstruction of the test vehicle obtained from the COLMAP software in this research can provide the quality standards necessary to effectively evaluate the causes of an accident. If a mobile phone stabilizer is used, then videogrammetry results can be as accurate as the ordinary photogrammetric approach using still images [21]. It has been established that quality control during image acquisition is crucial for accurate photogrammetric 3D reconstruction results.

In particular, blurred images may be found in extracted video frames in videogrammetry. The process of detecting blurred images is necessary to prevent low-quality images from being used in a 3D reconstruction [26]. In this experiment, the assessment of blurred images using the Laplacian function showed improved image quality in terms of sharpness when a mobile phone stabilizer was used. Although videogrammetry offers a reduction in data collection time compared to close-range photogrammetry, the use of still imagery is simpler because it does not require additional equipment or methods (e.g., camera calibration as described in section 3.1). However, it is time dependence and has constrain on the data collection process for traffic accident investigation of damaged vehicles. Thus, videogrammetry with a stabilizer is an alternative method that can be used for 3D model reconstruction of evidence in forensic science.

Photogrammetric processing using the COLMAP software based on SFM workflow provides a semi-automated processing within a user-friendly environment for forensic police officers. However, the design of a photogrammetric network for data collection can enable the appropriate reconstruction of a 3D vehicle model. Hence, a basic knowledge of image acquisition is required for a forensic police officer to capture suitable images for the photogrammetric approach in a traffic accident investigation. Basically, a convergent photogrammetric network and sufficient overlapping (80-90%) of each image directly affect the results of the damaged vehicle 3D model reconstruction. Image acquisition should cover the complete circumference around the damaged vehicle with two or three fully circular configurations at different heights to generate a sufficiently detailed 3D model of the damaged vehicle. Furthermore, additional images focusing on the damaged areas from a viewpoint above the vehicle were used to provide detailed 3D information on damage to each vehicle essential to the collision trajectory analysis. Consequently, the use of these additional images inevitably resulted in longer data processing times. However, this problem can be overcome using higher performance computing power to process the larger data files.

The benefits of inspecting damage using the 3D vehicle model include measuring the damage directly in the 3D point cloud after an accident. However, in evaluating the completeness of the 3D reconstruction outcomes obtained from the COLMAP software in each approach, there were some void areas in the 3D point cloud, such as the hood, roof, trunk, and doors. One explanation for these void areas is that there was insufficient recognition of the vehicle surface textures, causing the appearance of an absent surface. This limitation might be insignificant for traffic accident investigation of damaged vehicles because obvious traces of damage can be visually inspected from the imagery evidence. Furthermore, shiny or reflective vehicle surfaces can create difficulties for a 3D reconstructed vehicle model [2], so these models can be more susceptible to the outliers from photogrammetric results. The use of a circular polarizing filter (CPL) with a mobile phone camera is highly recommended for image collection [27] because it could help remove reflections from the vehicle surface and provide higher quality images when using the photogrammetric approach.

In the collision trajectory analysis of the actual traffic accident, the trajectory assessment after the collision was conducted using a computer-based simulation that compared the 3D models of both damaged vehicles. The collision reconstruction technique and the events that led to the collision can effectively enable 3D documentation for trajectory analysis in the accident investigation [11]. This is especially important in the case of collision trajectory analysis for large vehicles. The traditional forensic police method for providing accurate details is tedious and more difficult than this new technique. The processes currently used by investigators require a tow truck for assistance when the alignment of large damaged vehicles is needed. This study has shown that 3D reconstruction of damaged vehicles is a potential approach to investigating actual accidents.

Moreover, the unmanned aerial vehicle (UAV) photogrammetry can deliver additional 3D accident scene evidence to provide a more precise understanding of a traffic accident. UAVs allow for a more accurate simulation when using the reconstruction technique, providing images that can overlay the results of a collision trajectory analysis of a 3D traffic accident scene [4]. The use of UAVs and smartphones in the photogrammetric approach also has enormous potential for in-situ traffic accident investigation [13].

6. Conclusions

This study has demonstrated the potential of 3D reconstruction of forensic evidence for traffic accidents. Evidence collection from imagery that utilizes an affordable mobile device, open-source photogrammetric software, and off-the-shelf technology offers a low-cost approach for modeling damaged vehicles for traffic accident investigation. In particular, this innovative photogrammetric approach can employ semi-automated processing to generate a 3D model of a damaged vehicle. These methods can greatly benefit non-photogrammetrists, such as forensic police officers. The results show that 3D vehicle models can yield centimeter-level accuracy (approximately 2-3 cm), indicating enormous potential for assessing vehicle damage. Moreover, the 3D simulation of a traffic accident scene was obtained using a computer-based technique comparing the damage to each vehicle to analyze the collision trajectory. In future research projects, it is necessary to improve the quality of the 3D vehicle model outcomes. For example, a CPL filter should be used for image acquisition and post-image processing before 3D reconstruction to reduce outliers in point clouds. The continued development and eventual implementation of a photogrammetry-based system for traffic accident investigation by forensic police can yield 3D information to document forensic evidence used in trial proceedings.

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