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The Placement of Digitized Objects in a Point Cloud as a Photogrammetric Technique

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Abstract

The frequency of video-capturing collision events from surveillance systems are increasing in reconstruction analyses. The video that has been provided to the investigator may not always include a clear perspective of the relevant area of interest. For example, surveillance video of an incident may have captured a pre- or post-incident perspective that, while failing to capture the precise moment when the pedestrian was struck by a vehicle, still contains valuable information that can be used to assist in reconstructing the incident. When surveillance video is received, a quick and efficient technique to place the subject object or objects into a three-dimensional environment with a known rate of error would add value to the investigation. In addition, once the objects have been placed into the three-dimensional environment, the investigator would then be able to observe the physical evidence and environment from any perspective, including viewing and measuring what cannot be seen in the video perspective. In this research, the proposed photogrammetric technique of visually placing objects within three-dimensional laser scans will be evaluated. This research aims to quantify the rate of error of taking measurements of these objects to known fixed reference points both in and out of view of the camera, and provide an efficient technique that can be employed by reconstructionists using only one software package. As a result of this research, the authors have developed an expedient, less time-intensive photogrammetric technique for the placement of three-dimensionally scanned objects and environments. This technique can take less than half of the time of a conventional photogrammetric solution.

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Introduction

When an investigator is asked to reconstruct an incident, there may be limited data available to perform the analysis. As such, the limited available evidence, specifically the relative positions of the subject objects relative to permanent, fixed points, can make it challenging to accurately reconstruct the incident. Thus, the physical evidence that has been documented becomes more valuable, and therefore more scrutinized. In certain situations, an investigator may be limited to only post-incident photographs taken after a vehicle or other object has already been moved from its post-incident position. Other times, video of the subject incident is available. In these cases, photogrammetric methods are useful and valid approaches for determining the relative locations of moving or stationary objects to permanent, fixed points within the photographs or video.

Previously, receipt of video of an incident was an unexpected but beneficial addition to the materials received. With the proliferation and widespread use of surveillance cameras, DashCam recorders, and cellular phones capable of capturing high-quality video, receipt of video is becoming more common as part of the discovery package received by investigators. As opposed to answering more questions about the incident, the receipt of video often prompts more inquiries about the specifics of the event in question. Thus, an investigator is often tasked with answering questions about what cannot be seen in the video; the perspective that can be viewed provides the bases to answer these inquiries.

The receipt of surveillance video as part of an investigation typically provides an additional benefit over other video sources. Surveillance cameras are often mounted as fixed objects in a specific location relative to the accident scene. Thus, the physical location of the surveillance camera relative to the incident in question is unlikely to change over time. Although verification of this permanence can often be confirmed through Google Maps Streetview perspectives, verification of a surveillance camera's location and orientation can best be confirmed through a physical inspection of the site.

In one sense, the receipt of surveillance video can simply be considered a set of "photographs" for the reconstructionist to utilize during their analysis. As such, photogrammetric techniques can be utilized to take measurements of the objects observed in the surveillance video [1, 2, 3]. The aforementioned relative permanence of the surveillance camera location, however, eliminates one workflow that needs to be accounted for as part of a photogrammetric analysis of post-incident photographs - the physical location of the camera itself.

As video and high-quality surveillance cameras have become more common, the ability to three-dimensionally digitize the area the camera perspective has captured has become significantly easier. The advent and widespread adoption of three-dimensional laser scanning has fundamentally changed an investigator's ability to quickly and accurately digitize incident locations. A comprehensive, colorized, three-dimensional digitization of the incident location, which would have seemed nearly impossible to cost-effectively accomplish previously, can now be performed by a single operator in a matter of minutes. Myriad peer-reviewed studies have been published that use laser-based techniques as the "control", concluding that the quality of the data acquired from three-dimensional laser scanners is high and the measurements taken from the scans are precise [4, 5]. Coupled with the availability and prevalence of surveillance video, the technological advances of three-dimensional laser scanning provide an investigator powerful tools to analyze incidents.

Previous research has investigated the integration of three-dimensional laser scanning and photogrammetric techniques. Coleman staged a collision on both planar and curved surfaces to investigate the accuracy and efficiency of various photogrammetric techniques. The research concluded that the slowest methodology employed was the use of PhotoModeler software. Techniques that were more efficient, such as photograph rectification of point cloud data, failed to provide a compelling visual for any object that had more than two dimensions, i.e. a motorcycle helmet compared to a skid mark [6]. Carter investigated the use of point clouds from conventional laser scanners and unmanned aerial vehicles to camera match scene evidence. Although specific times for the methodologies were not provided, the techniques required the use of more than one software program to process and evaluate the data [7].

This research aims to outline and validate the methodology for utilizing surveillance video from an incident to place vehicles, or any other object, quickly and efficiently into a registered point cloud generated from three-dimensional laser scans of an incident site utilizing only one software package. The potential benefit of this technique is an efficient and time-saving methodology compared to other photogrammetric techniques. For example, the authors have found that this technique can take less than half of the time that a conventional photogrammetry project in a software package such as PhotoModeler can take. In addition, a compelling and geometrically-accurate three-dimensional visual of the evidence at issue has been created that can be presented to a jury at trial.

Another benefit of the methodology is that it utilizes only one piece of software. The photogrammetric technique in this research can be likened to on-site photogrammetry or reverse camera projection [8], with the important distinction that the on-scene work associated with those techniques is now taking place in a three-dimensional computer environment. After the objects are placed in the three-dimensional environment, measurements can then be taken to fixed reference points in the environment, like crosswalks or utility poles, which can either be observed in the surveillance video or are out of the video's range.

While there are other three-dimensional laser scanners and software packages available, this research utilized and evaluated FARO three-dimensional laser scanners and SCENE software. As one of the technique's main benefits is the time savings compared to other photogrammetric techniques, the timeframe to acquire spatial information utilizing this methodology will be quantified.

Methodology

To validate the technique, a series of six hypothetical scenarios were devised based on real-world cases the researchers have investigated. In each scenario, a vehicle or vehicles were driven into a position relative to a simulated scene attribute such as a painted line simulating a crosswalk or a simulated centerline. Two surveillance cameras captured the motion involved with the placement of each vehicle in the six staged scenarios. The site used for the testing was the rear parking lot of the Lingohocken Fire Company in Wycombe, Pennsylvania. A 2013 MINI Countryman and a 1997 E-One Fire-Rescue Apparatus (herein known as the Fire Truck) were utilized.

For each of the six scenarios, two researchers who were uninvolved with the validation of the technique took longitudinal and lateral physical measurements of scene attributes. The measurements included distances from the vehicles to fixed objects within the scene, or measurements between the two vehicles, utilizing two 25-foot steel measuring tapes. These control measurements were withheld from the two researchers who were evaluating the technique. The control measurements involved measurements that could and could not be directly observed in the surveillance video. These 18 physical longitudinal and lateral measurements would serve as the basis for the accuracy of the technique. Although two different surveillance cameras recorded each scenario, only one perspective was utilized per scenario to simulate the receipt of one video during an investigation (Table 1).

After the scenarios were staged and the physical measurements were taken, the surveillance video was secured from the Lingohocken Fire Company security system. The two researchers utilized three-dimensional laser scanners to create geometrically accurate three-dimensional point clouds of the incident site and vehicles. A FARO Focus^{3D} X330 laser scanner was used to scan the incident site at 11 different locations in the vicinity of the two surveillance cameras. After the scanning was completed, FARO SCENE software (versions 5.5.3.16 and 7.1.0.12) was used to register the scans of the

TABLE 1 Description of simulated scenarios.

Scenario	Camera #	# of Measurements	Description of Simulated Scenario
1	6	2	Fire Truck positioned outside of painted marked crosswalk
2	6	2	Fire Truck positioned inside of painted marked crosswalk
3	6	2	MINI positioned outside of painted marked crosswalk
4	6	2	MINI positioned inside of painted marked crosswalk
5	5	6	Fire Truck and MINI positioned parallel to one another in the same direction
6	5	4	Fire Truck and MINI positioned parallel to one another in the opposite direction

incident site to create the same three-dimensional digital environment that the surveillance cameras' video captured (Figure 1).

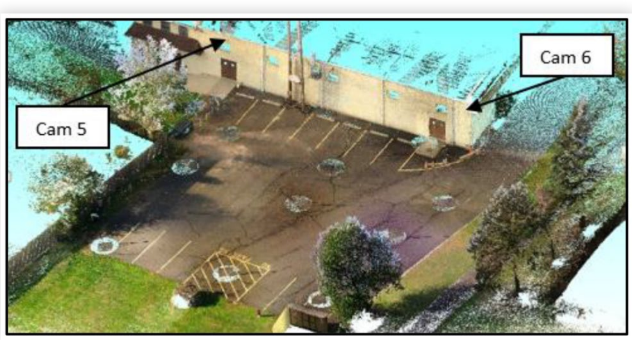
Similarly, using both a FARO Focus^{3D} S120 and a FARO Focus^{3D} X330 3D laser scanner, separate scans of the MINI and Fire Truck were performed. Each vehicle was individually compiled in the SCENE software as a separate project. Using clipping boxes, both the MINI and Fire Truck were saved and exported individually as separate .e57 files (Figure 2a and 2b).

Depending on the scenario, either one or both of the vehicles were imported as .e57 files into the three-dimensional point cloud of the incident site for analysis. After the appropriate vehicle or vehicles were imported into the incident site, the vehicles were moved, rotated, and adjusted to match the available surveillance perspective for the given scenario. It is important to note that this research focused on utilizing still frames of the static objects that were observed within the available surveillance perspective. The research focused on quantifying the positions of final rest of the vehicles, not determining the positons of moving objects over time. The location of fixed reference objects relative to the vehicles that were visible in the still frames from the surveillance video, such as painted lines, crack seals, utility poles, and curbs in Scenario 6, for example, were used to place the vehicles in the SCENE software so that they best-matched the location observed in the surveillance video by visual approximation. Clipping boxes were utilized throughout the workflow to assist in the best-fit placement of the vehicles relative to the location of unique fixed reference objects (Figure 3a through 3c).

The two researchers independently compiled the three-dimensional incident site and placed the vehicles for each scenario without the input or influence of the other researcher. This was purposely done to demonstrate and validate whether different individuals' methodologies can produce similar results.

To illustrate the workflow, Scenario 1, the Fire Truck outside of the crosswalk, will be analyzed to document the placement of one vehicle within the three-dimensional environment. Figures from all six scenarios are presented in Appendix A. The Fire Truck was driven into a position outside of a simulated marked crosswalk in Scenario 1 (Figure 4).

FIGURE 1 Elevated perspective of incident site in SCENE software depicting the locations of the surveillance cameras.



The position of the Fire Truck and crosswalk were selected so that the surveillance camera could not directly observe the front of the Fire Truck nor the crosswalk line. A screen capture still image of the Fire Truck at its point of rest in the surveillance video was taken for comparison purposes with the three-dimensional workflow. The unobserved simulated crosswalk is in front of the Fire Truck and to the right of the available perspective in Scenario 1 (Figure 5).

Utilizing the fixed reference points observed within the available surveillance video, the digitized .e57 file of the Fire Truck was placed into the three-dimensional project point cloud of the incident site. The Fire Truck was moved within the three-dimensional project point cloud to match the position observed in the surveillance video until a best-fit was achieved.

Using the 3D camera tool within SCENE, the perspective of the surveillance camera was matched by visual approximation with the SCENE software to demonstrate the substantial similarity of the placement of the Fire Truck within the scene. This perspective-matching was achieved by placing a virtual camera in the SCENE software in the same location as the scanned surveillance Camera 6. Surveillance Camera 6 could be located precisely in the SCENE software because it was scanned in as part of the registered point cloud (Figure 6).

Finally, the researchers were given a list of the physical measurements for each scenario that needed to be measured within the SCENE software. For Scenario 1, the front bumper of the Fire Truck to the outside of the painted crosswalk line was measured for the longitudinal control measurement. All measurements within the project point cloud utilized the scan point or object measuring tool within the SCENE software. For the lateral control measurement, the left side of the Fire Truck was measured to the center of a traffic cone that was placed to the left of the Fire Truck. This cone could not be observed in the available surveillance perspective (Figure 7).

For the testing, a longitudinal measurement was defined as any measurement taken utilizing a vector which was parallel to the vehicle centerline. A lateral measurement was defined as any measurement taken with a vector which was perpendicular to the vehicle centerline.

Each scenario was completed using the methodology outlined above. Figures 8 through 11 illustrate placing two vehicles within the digitized three-dimensional environment for Scenario 5, two vehicles traveling in the same direction.

FIGURE 2A Individual figure of the Fire Truck as an .e57 SCENE file.

FIGURE 2B Individual figure of the MINI as an .e57 SCENE file.

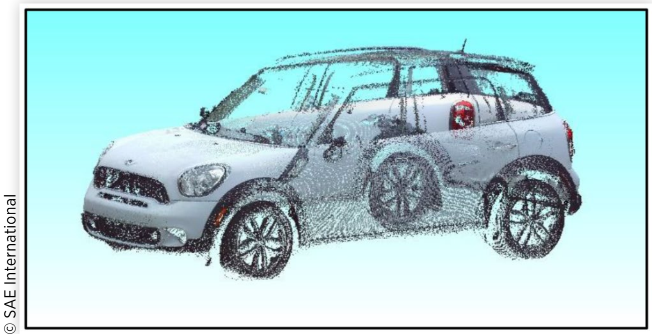


FIGURE 3A Screen capture of surveillance camera perspective in Scenario 6.

Results

Eighteen measurements were taken for this study which were then divided up into two categories: (1) longitudinal and (2) lateral measurements. Each of the two researchers used techniques independent of the other researcher's influence to determine the experimental value of the measurements taken using the FARO SCENE software.

Measurements were taken inside of a 450.0″ × 419.2″ area of the simulated scene. Figure 12 illustrates the area where the measurements were taken, i.e. the measurement box, with respect to the geometric locations of the two surveillance cameras utilized in the research. The furthest measurement from Camera 6 was Scenario 2, Measurement Number 3, which was 656.1 inches away from the camera. Likewise, the furthest measurement from Camera 5 was Scenario 6, Measurement Number 18, which was 452.6 inches away from the camera.

Table 2 displays the tabulated data of the thirty-six experimental values obtained by the two researchers using the SCENE software and eighteen reference measurements obtained using conventional measuring techniques. Longitudinal measurements are blue, and lateral measurements are orange. The 'Ref. Actual' column lists the control measurements taken utilizing the 25-foot steel tapes by the researchers uninvolved with the validation of the technique to the nearest quarter of an inch. The columns 'SH' and

FIGURE 3B Utilizing clipping boxes as part of the workflow for Scenario 6.

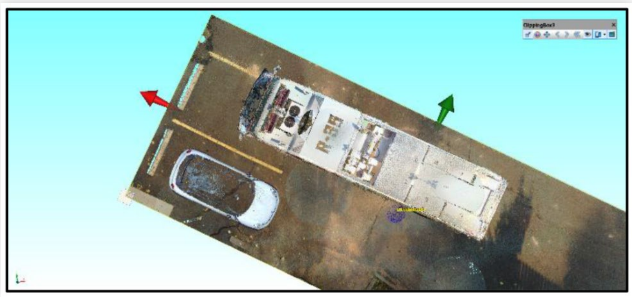


FIGURE 3C Identification and matching of scene attributes observed in the surveillance video to the scene attributes observed in the registered point cloud for Scenario 6.

FIGURE 4 Front of the Fire Truck outside of simulated crosswalk in Scenario 1.

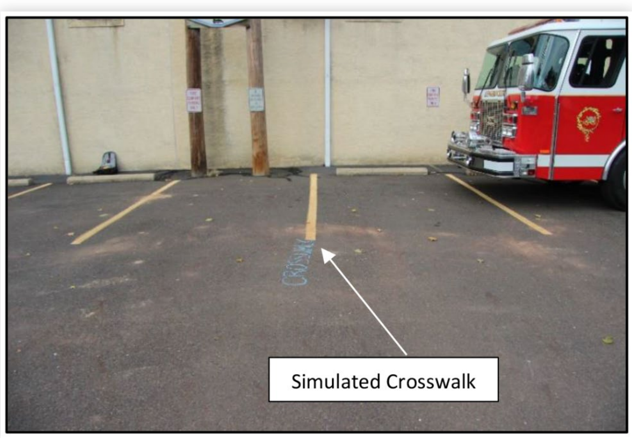


FIGURE 5 Screen capture of Surveillance Camera perspective for Scenario 1.

FIGURE 6 Surveillance perspective within the SCENE software for Scenario 1.

FIGURE 7 Left side of Fire Truck and cone for lateral control measurement in Scenario 1.

'GML' list the measurements, delta, and percent error from this research utilizing the proposed technique. The 'Measurement Distance' column reported the furthest distance from the surveillance camera to the termination of the measurement acquired in inches. Finally, the 'Visible' column reported if all (Y), partial (P), or none (N) of the measurement's beginning or end points could be viewed in the surveillance perspective. Further details are included in Appendix B.

The longitudinal and lateral measurements generated from the two researchers were compared to the actual reference values and analyzed in terms of percent error and root-mean-square-error using the following equations:

$$\%\ Error = \frac{|Actual - Experimental|}{Actual} \times 100$$

and,

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}\left(Actual_t - Experimental_t\right)^2}{n}}$$

where $Experimental_t$ is the set of experimental data which corresponds with $Actual_t$, the set of data retrieved during the physical examination of the scene and vehicles.

Tables 3 and 4 display the average percent error and the root-mean-square error of the data, respectively.

The percent error of the measurements was also reported in distance-based subsets based on the camera-to-measurement distance (Table 5).

Likewise, the percent error of the measurements was also reported by sorting the data based on the measurement's visibility. Measurements were coded 'Yes' when both the beginning and end points of the measurement was visible, 'Partial' when only one of the termination points was visible, and 'No' when neither point was visible in the surveillance camera perspective (Table 6).

Lastly, the time required to perform the technique was quantified. On average, approximately two to three hours was required from the initial processing of the scans after they were acquired to the final placement and measurement of the vehicles relative to fixed objects. One software package, FARO SCENE, was utilized in the workflow (Table 7).

FIGURE 8 MINI and Fire Truck traveling in same direction for Scenario 5.

FIGURE 9 Screen capture of surveillance camera perspective for Scenario 5.

FIGURE 10 Workflow for matching the scene attributes observed in the surveillance perspective to the placement of the .e57 files in the registered point cloud for Scenario 5.

Discussion

With an average error of 8.7 percent, the results of this research demonstrated a sufficient and acceptable accuracy for validating this technique in the accident reconstruction and scientific communities [9, 10, 11, 12, 13]. The results of this research confirmed that the technique can accurately place objects in their three-dimensional environment based on a review of surveillance video to an average lateral and longitudinal root-mean-square-error of less than six inches.

Importantly, this research quantified the accuracy and efficiency of using this technique to measure the distance between objects that cannot be seen in the provided surveillance video. Measurements like these, such as the distance between the front of

FIGURE 11 Surveillance perspective of the final placement of the three-dimensional objects within the SCENE software for Scenario 5.

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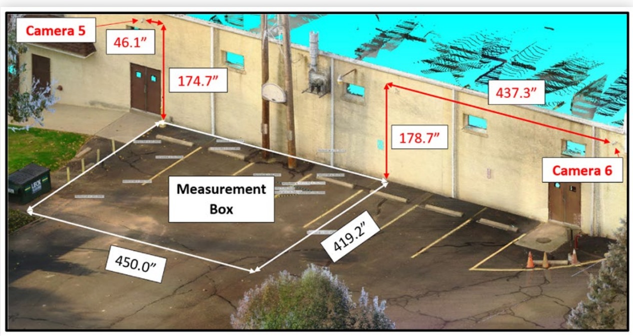
FIGURE 12 Position of surveillance cameras relative to the area of the simulated scene where measurements were obtained.



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the Fire Truck and a marked crosswalk in Scenarios 1 and 2, represent a novel application of this technique. With an average longitudinal error of 11.9 percent, an average lateral error of 5.6 percent, and an average overall error of 8.7 percent, these known rates of error can guide the investigator when attempting to quantify the potential error of similar analyses. These findings expand the area that investigators can accurately measure to outside the field of vision of the surveillance video even when an object is only partially visible in the acquired perspective.

While each investigator may take differing nuanced approaches in the workflow, their results may be equally accurate. This is an important confirmation for the technique, as there are often multiple paths to arrive at the same destination. Individual researchers achieving accurate and consistent results was as important a part of this research as the validation of the technique itself. Specifically, the two researchers had similar average longitudinal percent errors and longitudinal root-mean-square-errors.

The average lateral measurements were more than twice as accurate as the average longitudinal measurements. The accuracy of the technique is dependent on the quantity, quality, and location of fixed reference objects that can be observed in the camera perspective. In this research, where an objective was to measure and quantify the error of longitudinal distances of unseen objects a significant distance from the camera, increased uncertainty in the longitudinal direction was expected and observed. This was expected as there are often more unique fixed reference points in the lateral direction (i.e. lane lines parallel to a vehicle centerline), compared to the longitudinal direction (i.e. crosswalks).

Although the delta of Scenario 4, Measurement 7, was 4.3 and 9.6 inches for researchers SH and GML, respectively, the percent error associated with the measurements was significant. This does not invalidate the technique, rather, the relatively small control measurement of 14 inches and the size of the respective deltas magnified the otherwise normal delta, especially when compared to the average root-mean-square-error. Careful consideration and recognition of the error associated with the technique needs to be applied when attempting to apply this methodology to small magnitudes.

As expected, the average error of the measurements increased as the measurement distance from the surveillance camera increased. That is, measurements that were taken closer to the camera were more precise than measurements that were taken further from the camera's physical location. For measurement distances of zero to 600 inches (50 feet) from the surveillance camera, the average error was only 4.6 percent. Furthermore, the precision of measurements increased when both the beginning and end points of the measurement were visible.

Camera locations that are more vertical with respect to the ground plane they are capturing, i.e. surveillance cameras that are positioned higher off of the ground, produce more easily visible fixed reference objects that lead to increased accuracy of the technique. Consideration of the angle of incidence needs to be taken into account by the investigator.

Utilizing an analog control methodology to verify the accuracy of the technique, i.e. two steel measuring tapes, was a decision made based on the expedience of acquiring the control points via this method. As the Fire Truck and parking lot of Lingohocken Fire Company were out of service while testing was conducted, the expedient return of the apparatus and parking spaces back into service was a functional limitation of the research. While the measuring tapes provided a less precise comparison than a methodology like

TABLE 2 Master results from testing.

Scenario (Meas#)	Type of Meas	Units (inches) Ref. Actual	SH	GML	Delta (in) SH	GML	% Error SH	GML	Measurement Dist (in)	Visible
1 (1)	Long	86 3/4	78.3	85.8	−8.5	−0.9	9.8	1.1	615.4	N
1 (2)	Lat	115 1/4	106.1	107.8	−9.1	−7.5	7.9	6.5	562.7	N
2 (3)	Long	38	49.0	45.9	11.0	7.9	28.8	20.7	656.1	N
2 (4)	Lat	117 3/4	103.3	117.5	−14.5	−0.3	12.3	0.2	562.7	N
3 (5)	Long	92 1/2	86.8	83.5	−5.7	−9.0	6.2	9.7	615.4	N
3 (6)	Lat	113 3/4	110.8	109.7	−3.0	−4.1	2.6	3.6	562.7	P
4 (7)	Long	14	18.3	23.6	4.3	9.6	30.7	68.4	633.4	N
4 (8)	Lat	114 1/4	113.8	105.3	−0.5	−8.9	0.4	7.8	562.7	P
5 (9)	Lat	51 1/4	56.5	51.0	5.2	−0.3	10.1	0.5	383.3	P
5 (10)	Lat	49	52.1	46.4	3.1	−2.6	6.3	5.3	438.7	P
5 (11)	Lat	16 3/4	19.2	16.5	2.5	−0.3	14.9	1.6	424.1	P
5 (12)	Lat	68 1/2	71.4	66.8	2.9	−1.7	4.2	2.5	395.9	P
5 (13)	Long	148 3/4	153.1	148.2	4.4	−0.5	3.0	0.3	311.8	Y
5 (14)	Long	100 1/2	103.0	99.0	2.5	−1.5	2.4	1.5	351.2	Y
6 (15)	Lat	44	51.4	43.6	7.4	−0.4	16.8	0.8	285.8	P
6 (16)	Lat	16 1/2	16.3	17.5	−0.2	1.0	1.5	5.9	205.0	Y
6 (17)	Long	78 1/4	76.5	78.9	−1.7	0.6	2.2	0.8	312.2	Y
6 (18)	Long	174 1/4	169.4	171.7	−4.9	−2.6	2.8	1.5	452.6	P

TABLE 3 Average percent error from testing.

SH longitudinal average % error:	10.7	%
GML longitudinal average % error:	13.0	%
Longitudinal average % error:	11.9	%
SH lateral average % error:	7.7	%
GML lateral average % error:	3.5	%
Lateral average % error:	5.6	%
Average error:	**8.7**	**%**

TABLE 4 Root-mean-square-error from testing.

SH longitudinal RMSE:	6.1	inches
GML longitudinal RMSE:	5.5	inches
Longitudinal average RMSE:	5.8	inches
SH lateral RMSE:	6.4	inches
GML lateral RMSE:	4.0	inches
Lateral average RMSE:	5.2	inches
Average RMSE:	**5.5**	**inches**

TABLE 5 Percent error sorted by measurement distance from the surveillance camera.

Subset	n	Percent Error (%) SH	GML	Average
200-400 (in)	7	5.7	1.8	3.8
400-600 (in)	7	6.7	3.8	5.3
600+ (in)	4	18.9	24.9	21.9

TABLE 6 Percent error sorted by the visibility of the measurement when viewed from the surveillance perspective.

		Percent Error (%)		
Subset	**n**	**SH**	**GML**	**Average**
Yes	4	2.3	2.2	2.2
Partial	8	7.3	3.0	5.1
No	6	16.0	17.8	16.9

TABLE 7 Approximate time for the three-dimensional photogrammetric workflow.

Task	Time
Scanning of Object(s)	0.5-2 hours
Scanning of Scene	0.5-1.5 hours
Processing of Scans	0.5-2 hours
Placement of Object(s)	0.5-1 hour
Measurements	15 minutes

scanning-in-place, the speed of the acquisition of these control points utilizing measuring tapes was a tangible benefit. It is possible that future studies that employ this methodology while utilizing more accurate control measurements may achieve more accurate results with a lower range of error.

All control measurements were taken parallel or perpendicular to the longitudinal axis of the respective vehicles to ensure a sufficiently accurate baseline reference setup. Control measurements were taken between the vehicles in Scenarios 5 and 6, in order to simulate a “who crossed the centerline” scenario, and to fixed objects in all scenarios within the simulated scene. Taking advantage of fixed objects is not only a common photogrammetric technique, but ensured a sufficiently accurate baseline reference setup.

While other photogrammetric techniques may yield a higher degree of precision, the time requirement associated with those methodologies may be as many as two to three times the investment of this technique. Furthermore, these photogrammetric methodologies may involve managing multiple pieces of software to construct the photogrammetric solution. The efficiency of this technique compared to a conventional photogrammetric solution is one of the main benefits. Furthermore, compelling and scaled three-dimensional visuals can be created based on the technique that have a known rate of error.

Careful consideration needs to be taken when the surveillance perspective involves soft targets, i.e. foliage, native vegetation, etc., that can potentially change with time and season. Although these objects certainly do not preclude application of this technique, they must be dealt with on a case-by-case basis.

Each scene is unique. While this study presents a specific error range for evidence placement, there are many factors to consider that may either positively or negatively affect the results. These factors can include the proximity of the camera or video camera to the evidence to be placed from video, the number of unique landmarks that can be used as a reference and their proximity to evidence to be placed from video, the number of cameras capturing the event, the resolution of video frames, the angle of incidence, and lens distortion and pixel aspect ratio correction.

The purpose of this research was to evaluate the technique when only one surveillance perspective was received by an investigator. The receipt of more than one perspective of the same area, like receiving both Camera 5 and Camera 6 for each scenario, would only enhance the accuracy of the technique.

While this research focused on the static positions of objects at their points of final rest utilizing still images from the surveillance video, this does not preclude the application of this technique to quantifying objects in motion to determine position and velocity using a frame-by-frame analysis. Potential uncertainties associated with acquiring still frames from video, such as motion blur, must be accounted for when applying this technique in such a way.

Although this research focused on video, the same methodologies apply to quantifying photographs using the same principles. The screen captures and corresponding still images from the video represent one frame from the video, which is essentially the same as a photograph. The only additional step would be to solve for the camera location, using previously-published photogrammetric techniques.

Summary/Conclusions

1. The results of this research validated this photogrammetric technique as a sufficiently accurate tool for placing objects into a three-dimensional scene and measuring distances that can and cannot be seen in the available surveillance video perspective.

2. The average percent error associated with this technique was 8.7 percent. The average root-mean-square-error was 5.5 inches.
3. While each investigator may take differing nuanced approaches in the three-dimensional workflow, their results may be equally accurate.
4. Although this research focused on video, the same principles apply to quantifying object locations in photographs.
5. The expediency of this photogrammetric technique can be two to three times faster than conventional photogrammetric solutions.

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Appendix A

FIGURE A.1 Scenario 1, outside crosswalk, surveillance video (top) and perspective within the SCENE software (bottom).

FIGURE A.2 Scenario 2, inside crosswalk, surveillance video (top) and perspective within the SCENE software (bottom).

FIGURE A.3 Scenario 3, outside crosswalk, surveillance video (top) and perspective within the SCENE software (bottom).

FIGURE A.4 Scenario 4, inside crosswalk, surveillance video (top) and perspective within the SCENE software (bottom).

FIGURE A.5 Scenario 5, parallel same direction, surveillance video (top) and perspective within the SCENE software (bottom).

FIGURE A.6 Scenario 6, parallel opposite direction, surveillance video (top) and perspective within the SCENE software (bottom).

Appendix B

TABLE B.1 Description of control points and their visibility utilized in the research.

Scenario 1 Fire Truck Out of Crosswalk	**Meas. #**	**Type**	**Measurement**	**Meas. Distance from Camera**	**Meas. Visible?**
Center of Fire Truck front bumper to crosswalk; measurement along longitudinal axis of Fire Truck	1	Long	86¾ inches	615.4 inches	No
Left front door of Fire Truck to center of cone; measurement is perpendicular to longitudinal axis of truck	2	Lat	115¼ inches	562.7 inches	No
Scenario 2 Fire Truck Inside Crosswalk	**Meas. #**	**Type**	**Measurement**	**Meas. Distance from Camera**	**Meas. Visible?**
Center of Fire Truck front bumper to crosswalk; measurement along longitudinal axis of fire truck	3	Long	38 inches	656.1 inches	No
Left side of Fire Truck to center of cone; measurement is perpendicular to longitudinal axis of truck	4	Lat	117¾ inches	562.7 inches	No
Scenario 3 MINI Out of Crosswalk	**Meas. #**	**Type**	**Measurement**	**Meas. Distance from Camera**	**Meas. Visible?**
Center front of MINI to crosswalk line; measurement along longitudinal axis of MINI	5	Long	92½ inches	615.4 inches	No
Left front tire of MINI to center of cone; measurement is perpendicular to longitudinal axis of MINI	6	Lat	113¾ inches	562.7 inches	Partial - cone visible
Scenario 4 MINI Inside Crosswalk	**Meas. #**	**Type**	**Measurement**	**Meas. Distance from Camera**	**Meas. Visible?**
Center front of MINI to crosswalk line; measurement along longitudinal axis of MINI	7	Long	14 inches	633.4 inches	No
Left rear tire of MINI to center of cone; measurement is perpendicular to longitudinal axis of MINI	8	Lat	114¼ inches	562.7 inches	Partial - cone visible
Scenario 5 Same Direction (Fire Truck and MINI)	**Meas. #**	**Type**	**Measurement**	**Meas. Distance from Camera**	**Meas. Visible?**
Distance between 2 vehicles; measurement from left front door of MINI to right rear door of Fire Truck	9	Lat	51¼ inches	383.3 inches	Partial - right rear door of Fire Truck visible
Distance between 2 vehicles; measurement from left rear wheel (center hub) of MINI to right front of underside slide-out compartment on Fire Truck	10	Lat	49 inches	438.7 inches	Partial - right underside compartment visible
Distance between the right rear wheel of the MINI and the forward edge of the parking block	11	Lat	16¾ inches	424.1 inches	Partial - right rear wheel visible
Distance between the right rear door handle of the MINI and the outside stucco wall of Station 35	12	Lat	68½ inches	395.9 inches	Partial - right rear door handle of MINI visible
Center-left of the Fire Truck's front bumper to the center of three yellow bollards.	13	Long	148¾ inches	311.8 inches	Yes
Center front bumper of MINI to yellow parking line adjacent to the three yellow bollards.	14	Long	100½ inches	351.2 inches	Yes
Scenario 6 Opposite Direction (Fire truck and MINI)	**Meas. #**	**Type**	**Measurement**	**Meas. Distance from Camera**	**Meas. Visible?**
Distance between MINI and Fire Truck; measurement made starting at left front A-pillar door seam of MINI (above the 'ALL 4' emblem) to the center of the white stripe on the left front door of the Fire Truck	15	Lat	44 inches	285.8 inches	Partial - left front door of Fire Truck visible
Center of MINI's right real wheel to concrete pad located in front of Station 35 rear doors	16	Lat	16½ inches	205.0 inches	Yes
Center-left front bumper of the fire truck to the front of the second parking block	17	Long	78¼ inches	312.2 inches	Yes
Center front bumper of MINI over to wooden beams bordering the grass area beyond the LECK green dumpster	18	Long	174¼ inches	452.6 inches	Partial - wooden beam visible