

The Accuracy of an Optimized, Practical Close-Range Photogrammetry Method for Vehicular Modeling

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ABSTRACT

Three targeted vehicles of varying size were measured using an optimized, practical photogrammetry technique and the results were compared to measurements acquired via total station. The photogrammetry method included the use of a field-calibrated DSLR camera equipped with a fixed 20 mm lens, retroreflective targets sized for vehicular modeling, and a CNC-machined scale bar. Eight photographs were taken from proper angles and processed using a commercially available photogrammetry package. This data was merged with the total station data using a cloud-to-cloud registration process for point-to-point comparison of positional data. The average residual between corresponding photogrammetry and total station points was 1.7 mm ($N = 258$, $SD = 0.8$ mm) with a 95% confidence limit of 3.1 mm. Considering this low residual, one of the sample vehicles was re-measured using a high accuracy FaroArm for comparison to the photogrammetry technique. The average residual between corresponding photogrammetry and FaroArm points was 1.2 mm ($N = 83$, $SD = 0.56$ mm) with a 95% confidence limit of 2.1 mm. This research shows photogrammetry can be highly accurate and efficient with proper methodology, while also expanding on the photogrammetry literature database and improving confidence in the technique.

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INTRODUCTION

Photogrammetry is the science of extracting measurements from photographs. Within the accident reconstruction community, photogrammetry is typically used for measuring and locating roadway evidence (e.g. tire marks, gouges, final rest positions, etc.), or quantifying the amount of crush sustained by a vehicle. In many cases, photographs are taken with the intent of performing a photogrammetric analysis. In those situations, the camera is likely to be calibrated and its parameters known. Further, the objects to be modeled are often targeted using high contrast, easily identifiable targets. In other cases, the photographs were not originally taken for the purpose of photogrammetry, and for that reason, the parameters of the camera are not fully known and the objects of interest are not targeted. Analyses of the latter type are referred to as *unknown camera* projects, and are commonly encountered when working with police photographs to place scene evidence, or when using appraisal photographs to quantify crush. Exemplar vehicles, as those modeled in the subject research, provide the necessary control points and baseline measurements to perform this type of crush analysis. In any case, if two or more photographs of the object to be modeled exist, three-dimensional measurements can often be produced.

Many studies have been performed in pursuit of quantifying the accuracy of photogrammetry as it relates to modeling damaged and undamaged vehicles. These studies have also examined the accuracy of both known and unknown camera projects. Several of the foundational studies on the topic, which were undertaken prior to the advent of digital photography, show accuracies ranging from 10 to 50 mm [1,2,3].

Using a calibrated film camera and high-contrast non-retroreflective targets, Switzer et al. modeled a portion of a vehicle via photogrammetry and total station, and compared the results. Under optimal conditions, the authors observed an average residual of 2.3 mm, and maximum of 11.2 mm [4].

With an uncalibrated film camera and non-targeted vehicles, Fenton et al. were able to demonstrate accuracy between 0.4 and 2.0% (5 to 56 mm) when comparing photogrammetry results to published vehicle specifications [5].

Rentschler et al. utilized an optimized technique, using a calibrated digital camera (6 MP), retroreflective targets, defined scale, and over 34 photographs, to obtain deviations between photogrammetry and a

CMM (coordinate measuring machine) within ± 1 mm, with a maximum residual of 2.1 mm, when modeling a vehicle [6]. O'Shields et al. also utilized a calibrated digital camera (5 MP) to model exemplar vehicles and compared those models to measurements obtained using unknown camera projects of corresponding damaged vehicles [7]. Neither the exemplar nor the damaged vehicle were targeted for photogrammetry, yet the authors demonstrated accuracy of 8% at a 95% confidence level when comparing calculated EBS (equivalent barrier speed) to known EBS.

Employing a calibrated digital camera (6 MP) and retroreflective targets, Mills et al. demonstrated accuracy of 10 to 21 mm when comparing vehicular measurements obtained via photogrammetry to corresponding total station measurements [8]. The retroreflective photogrammetry targets in this study were not measured directly with the total station. Instead, a micro-prism was placed in front of the photogrammetry target.

Similarly, Randles et al. compared the accuracy of photogrammetry to total station measurements when modeling various portions of three vehicles [9]. The authors used high-contrast, but non-retroreflective targets, and several different digital cameras (6.1 to 12.1 MP), none of which were calibrated. A mean residual of 1 mm was observed, with a standard deviation of 10 mm, and a maximum residual of 20 mm.

The work above clearly demonstrates the potential for accurately modeling vehicles using photogrammetry techniques. The current research seeks to quantify the accuracy of a practical photogrammetry method for vehicular modeling, utilizing modern equipment and compiling effective techniques gathered from the investigations discussed above. Specifically, the subject research combines the following technique and items, which has not been examined previously:

- Retroreflective disc targets
- Retroreflective spherical targets visible in all photographs
- CNC-machined scale bar
- Modern digital camera (14.2 MP)
- Field-calibrated digital camera
- Expedient photography process consisting of eight camera stations
- Comparison of results to a total station with reported accuracy of ± 2.0 mm
- Comparison of results to FaroArm with reported accuracy of 0.124 mm

METHODOLOGY

Three vehicles of varying size (Table 1) were measured using the subject photogrammetry technique, and the results were compared to measurements obtained using a Sokkia SRX5X total station with reported accuracy of ± 2.0 mm. The Acura TSX was measured a second time via photogrammetry and those results were compared to measurements obtained using a FaroArm with reported accuracy of 0.124 mm.

Table 1. Vehicles measured using photogrammetry and total station, where L is overall length, and W is overall width [10].

Vehicle	Type	L (cm)	W (cm)
2011 Acura TSX	Sedan	471.4	183.9
2015 Chrysler Town & Country	Minivan	515.1	199.9
2007 Volkswagen GTI	Hatchback	421.1	176.0

Photogrammetry

Custom targets were designed for the research, comprised of a matte black 44.5 mm x 0.9 mm magnetic disc with a 25 mm white retroreflective vinyl center. A 3 mm circular cutout was created in the center of the vinyl using a CNC vinyl cutter, exposing an underlying area of high contrast to facilitate consistent reflectorless measurement of the target's center using the aforementioned total station, and consistent probing with the FaroArm (Figure 1). When exposed to a camera flash, the 3 mm portion of the target becomes invisible, resulting in an uninterrupted 25 mm target, contrasted by the black background, which is optimal for use within the photogrammetry software package employed here, PhotoModeler (v. 2015.1).

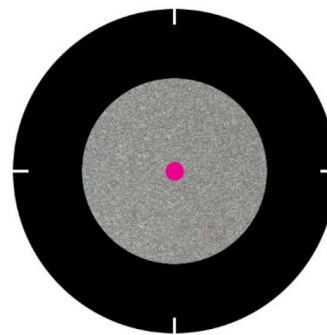


Figure 1. Custom target designed for the subject research.

The above targets were placed on the vehicles in a manner to create exemplar measurements for the purpose of a crush analysis, which is a common utilization of such modeling. As such, targets on the side of the vehicle were placed at the approximate mid-door height and on the rocker panel, or rocker panel molding. For the front and rear, the targets were placed on the bumper cover at a height that corresponds to the approximate mid-height of the underlying reinforcement beam, and on the leading and trailing edge of the hood and trunk, respectively. The majority of the targets were affixed to the vehicle magnetically, while those installed on plastic or aluminum components were mounted using reusable, 25 mm x 0.9 mm, adhesive disks. The targets do not mark or damage the subject vehicle in any manner, an important factor when attempting to obtain permission to model an undamaged specimen.

In addition, five 48 mm retroreflective spherical targets were placed on the roof of each vehicle, in an "X" pattern, to enhance the photogrammetric solution. These targets were visible from all photographs, and because the targets are spherical, the center can be consistently selected in each photograph (Figure 2).



Figure 2. Photograph of the targeted 2007 Volkswagen GTI, illustrating placement of disc targets, spherical targets, and scale bar.

The photogrammetry project scale was set using a CNC-machined, black-anodized, aluminum scale bar with two 25 mm circular cutouts separated by a distance of 114.3 cm (45.00 inches). 25 mm retroreflective vinyl discs were placed in the center of each cutout to increase contrast and selectability within PhotoModeler (Figure 3).



Figure 3. CNC-machined scale bar with retroreflective targets.

A Nikon D3100 camera (14.2 MP) with a fixed Nikon 20 mm f/2.8 AIS lens was used for the purpose of photogrammetry. The camera and lens were initially calibrated using PhotoModeler's calibration routine which relies on a 0.9 m square sheet comprised of a 144-target grid. Four of those targets are coded for the purpose of automation. The camera setup was further calibrated using 40 retroreflective targets arranged in a 4.8 m x 2.8 m grid meant to represent the size of a typical sport utility vehicle. Photographs of the grid were taken from various angles, and processed using PhotoModeler's *Camera Optimization* feature, also known as *field calibration*. In both cases, the camera was calibrated with the aperture fixed at f/11, while shutter speed was varied to create an appropriate exposure. The flash was forced to fire in all photographs to activate the retroreflective portion of the targets.

Eight hand-held photographs of the targeted vehicle were taken at the positions shown in Figure 4. Special care was taken to ensure all spherical targets were visible in each photograph. For that reason, minor deviations from the idealized camera position occurred. The photographs were taken from the approximate eye-height of the photographer (1.7 m), but changes in camera height were allowed to optimize contrast of the spherical targets, which are sensitive to background color/objects since, unlike the disc targets, they do not have an integrated contrasting background.

The photographs were analyzed using a semi-automated process within PhotoModeler. Specifically, the targets were selected using automated sub-pixel marking, but each target was referenced manually by the user. After processing and scaling, the measurements were exported for further analysis. In all cases, the maximum residual error was below 1.0 pixel. The point marking residual RMS for the Acura, Chrysler, and Volkswagen, was 0.168, 0.166, and 0.223 pixels, respectively. No high-residual points were removed or omitted.

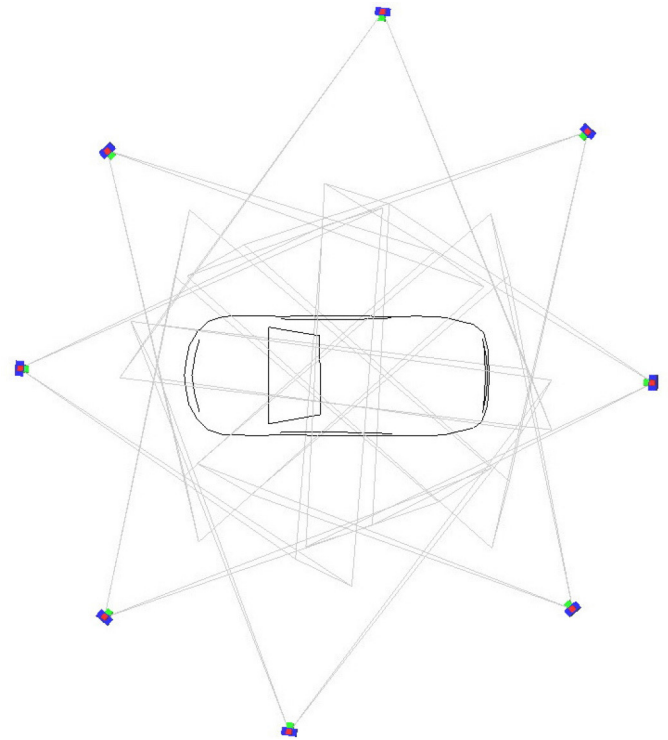


Figure 4. Camera positions for the eight photographs used to create the photogrammetry vs. total station model of the 2011 Acura TSX, including the field-of-view for each camera.

Total Station

Immediately after being targeted and photographed for the purpose of photogrammetry, each vehicle was measured using the total station described above. Four measurement positions were required to model the entire vehicle. To ensure optimal merging of the four data sets, all visible targets were measured and compared from each position. In addition, three targets, visible from all positions, were placed in a triangular fashion surrounding the vehicle to bolster data merging, which was accomplished using CloudCompare (version 2.6.1), a software package that is discussed further below [11].

FaroArm

The Acura was used as the foundation for additional analysis. Similar to the process above, the Acura was targeted and photographed for the purpose of photogrammetry. Subsequently, the center of each target

was measured using a FaroArm Fusion 3.0 meter CMM, (Figure 5). It was not possible to measure all targets from one measurement station. As such, the FaroArm had to be moved six times through the measurement process to capture the location of all targets.



Figure 5. View of the targeted Acura and FaroArm.

Data Comparison

Photogrammetry vs. Total Station

The resultant photogrammetry and total station point clouds were compared using CloudCompare. As discussed by Erickson et al., CloudCompare implements an Iterative Closest Point algorithm, where the position and orientation of each point cloud is varied until the point-to-point distance is minimized [12]. This methodology eliminates any subjectivity and allows for straightforward statistical analysis, since the results of the process are reported. In this case, the photogrammetry-based measurements were treated as one point cloud, and the total station data was treated as another. In other words, the clouds were not sub-divided in any manner. Additionally, though it is an option within CloudCompare, the scale of the photogrammetry-based and total station point clouds was **not** allowed to be adjusted in pursuit of a better fit.

Photogrammetry vs. FaroArm

Similar to above, the photogrammetry-based measurements were compared to the FaroArm data using CloudCompare. However, to eliminate any error associated with merging the six sets of Faro data, each set was compared directly to the corresponding photogrammetry-based measurements. For instance, the first Faro position contained 23 target measurements. That set of 23 measurements was compared to the corresponding photogrammetry-based measurements, without subdividing the photogrammetry point-cloud on any level.

RESULTS

Photogrammetry vs. Total Station

The residuals between the photogrammetry and total station measurements are summarized in Table 2. For a total of 258 points, the average residual between corresponding photogrammetry and total station points was 1.7 mm with a standard deviation of 0.80 mm, while the maximum residual observed was 4.6 mm.

Table 2. Results of the photogrammetry measurements versus those obtained via total station.

Vehicle	N	Avg. Residual (mm)	SD (mm)	Max Residual (mm)
Acura	83	1.9	0.92	4.5
Chrysler	85	1.7	0.74	4.6
Volks.	90	1.7	0.71	4.1
Total	258	1.7	0.80	4.6

A normal probability plot based on the photogrammetry / total station residuals was created to determine if normal distribution analysis techniques were appropriate for this data set (Figure 6). If the data is normally distributed, it will follow a straight line. As can be seen, the central portion of the curve follows the linear path quite well. However, deviations at the extents of the curve show the data is slightly skewed to the left, toward smaller residuals.

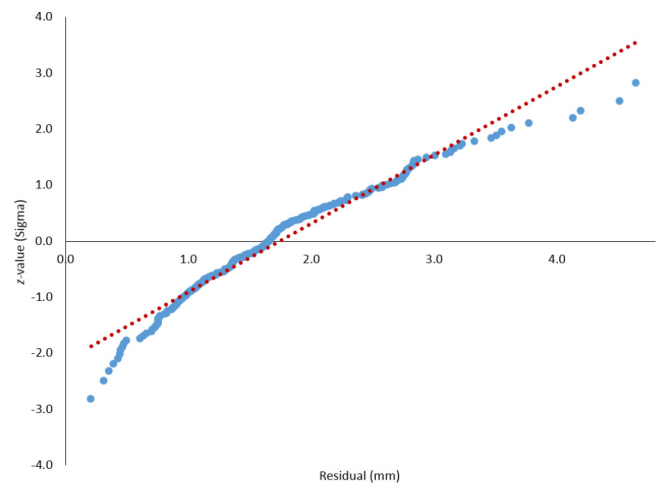


Figure 6. Normal probability plot of photogrammetry and total station point residuals.

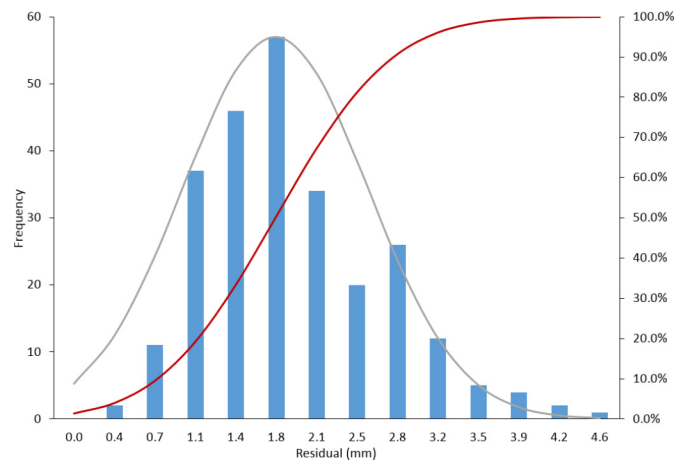


Figure 7. Histogram of photogrammetry and total station point residuals with normal distribution and cumulative probability plots overlaid.

This concept is also illustrated via Figure 7, which is a histogram showing the photogrammetry / total station residuals. Specifically, the frequency of the smaller residuals is higher than that of the larger residuals. Ultimately though, normal distribution analysis techniques were deemed appropriate for the data. This conclusion is supported by

by Figure 7, which also depicts the theoretical normal distribution and normal cumulative distribution plots combined with the residual histogram.

Knowing the average residual for the entire data set is 1.7 mm, and the standard deviation is 0.80 mm, it was determined that the 68% and 95% confidence intervals are 0.9 to 2.5 mm and 0.1 to 3.3 mm, respectively. The cumulative distribution plot above can be used to determine the probability that the residual will be below a certain value. For instance, 95% of the residuals are predicted to be below 3.1 mm.

Photogrammetry vs. FaroArm

The residuals between the photogrammetry and FaroArm measurements are summarized in Table 3. For a total of 83 points, the average residual between corresponding photogrammetry and FaroArm points was 1.2 mm with a standard deviation of 0.56 mm, while the maximum residual observed was 2.5 mm.

Table 3. Results of the photogrammetry measurements versus those obtained via FaroArm.

Vehicle	N	Avg. Residual (mm)	SD (mm)	Max Residual (mm)
Acura	83	1.2	0.56	2.5

Again, a normal probability plot based on the photogrammetry / FaroArm residuals was created to determine if normal distribution analysis techniques were appropriate for this data set (Figure 8). Aside from several points at the lower residuals, the FaroArm data followed a normal distribution quite well.

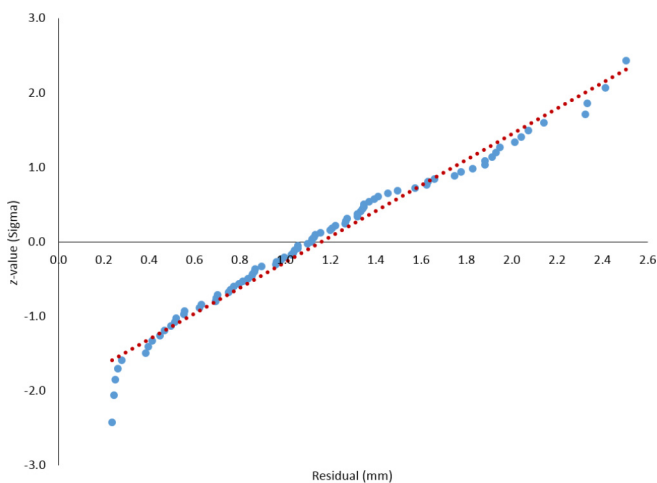


Figure 8. Normal probability plot of photogrammetry and FaroArm point residuals.

Figure 9 shows the histogram for the photogrammetry / FaroArm residuals along with the theoretical normal distribution and normal cumulative distribution plots. Knowing that the average residual for the entire data set is 1.2 mm, and the standard deviation is 0.56 mm, it was determined that the 68% and 95% confidence intervals are 0.6 to 1.7 mm and 0.0 to 2.3 mm, respectively. Again, the cumulative distribution plot above can be used to determine the probability that the residual will be below a certain value. Here, 95% of the residuals are predicted to be below 2.1 mm.

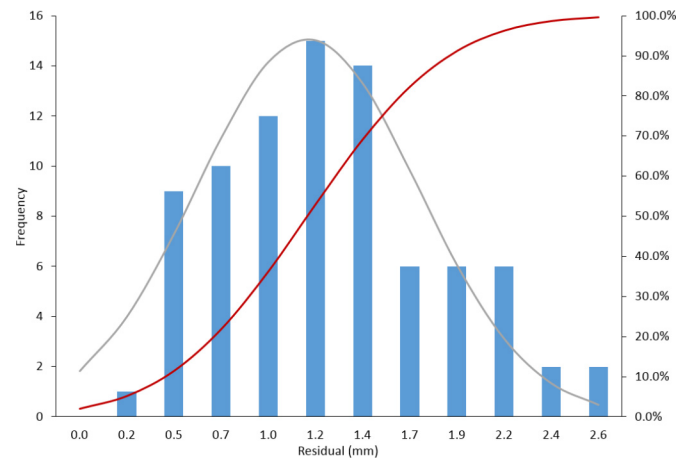


Figure 9. Histogram of photogrammetry and FaroArm point residuals with normal distribution and cumulative probability plots overlaid.

DISCUSSION

This research shows vehicles can be accurately modeled using the technique detailed above, which only requires eight photographs of the subject vehicle. Additionally, the process is expedient, inexpensive, measurements can be added to the project post-hoc, and only minimal training is required for the user. Regarding expediency; setup, photography, and teardown typically requires 20 to 25 minutes. Though, simpler vehicles often require only 15 minutes.

As detailed above, the average residual of the photogrammetry model compared to the total station and FaroArm was 1.7 and 1.2 mm, respectively. While the purpose of the research does not contrast dramatically when compared to prior efforts, the results are notably improved due to the targeting process. Namely, Switzer et al. found an average residual of 2.3 mm and a maximum of 11.2 mm between corresponding points mapped via photogrammetry and a total station (N = 29) [4]. In the subject investigation, the maximum residual observed in the total station comparison was 4.6 mm (N = 258). Additionally, the standard deviation in the Switzer study was 2.2 mm, but was reduced to 0.80 mm in this study. As outlined above, both the maximum residual and standard deviation dropped to 2.5 mm and 0.56 mm, respectively, when the FaroArm was used here (N = 83). The difference in results can be explained by several factors. Specifically, the targets used by Switzer et al. were not retroreflective, which increases target contrast and therefore consistent automated selection and accuracy. In addition, the total station surveying process was accurate to about +/- 6mm (compared to +/- 2mm here), and the images were transferred from film to Kodak Photo CD before processing. With the current widespread use and availability of digital photography, native digital images were used for processing in this study, and likely contributed to the improved results.

For further comparison, Rentschler et al. documented deviations between photogrammetry and CMM measurements within +/- 1 mm, with a maximum residual of 2.1 mm [6]. These results align closely to those observed here. In the current investigation though, only eight photographs were used to measure each vehicle. In contrast, Rentschler utilized at least 34 photographs to create the model. Unfortunately, the exact number of photographs used by Rentschler was not documented in that manuscript.

The subject results also agree with Randles et al., who found a mean residual between photogrammetry and total station measurements of 1 mm [9]. However, in that study, the authors found the standard deviation to be 10 mm and observed a maximum residual of 20 mm. In the subject research, the corresponding standard deviation and max residual (photogrammetry vs. total station) was 0.80 and 4.6 mm, respectively. This disparity is likely due to the fact that the cameras and photographers in the Randles study varied, the cameras were not calibrated, and at least one of the photographers was not trained, nor was he taking the photographs for the purpose of photogrammetry.

The subject technique was found to be more accurate than Fenton et al. demonstrated [5]. However, this difference is expected since Fenton did not use a calibrated camera or apply targets to the modeled vehicles. Similarly, the technique here was found to be more accurate than that demonstrated by Mills in 2005 [8]. While Mills utilized a calibrated digital camera and retroreflective targets, a micro-prism was placed in front of the target of interest when measuring their position via total station. This method is likely to introduce error and may explain the differences in observed residuals.

Since photogrammetry accuracy is often quantified as a ratio based on the distance between the camera and the modeled point, vehicles of varying size were used for this research. However, while the Chrysler was 22% longer and 14% wider than the Volkswagen, the average residuals were not substantially different.

It is important to distinguish between residual and error. Recall, the average residual between the photogrammetry and total station measurements was 1.7 mm. It may be tempting to call this an error; however, the total station used here has an accuracy of +/- 2.0 mm. For that reason, it is not appropriate to call the residual an error as the accuracy range of the instrument is greater than the average difference between corresponding photogrammetry and total station points. Similarly, while the FaroArm used here has a reported accuracy of 0.124 mm, the user must touch the probe (3mm sphere) to the center of the target, and while this can be done with high confidence due to the target design detailed above, it is not possible for the user to locate the center of the target perfectly in every instance. When dealing with values on the order of 1 mm, it is possible that a portion of that residual is a result of inconsistency when probing the target with the FaroArm. For that reason, the 1.2 mm average residual may also not be true "error." However, the FaroArm measurements are the most robust baseline available, and therefore it seems appropriate to use those measurements to establish error, not just residuals.

While the accuracy of the subject method was only quantified for undamaged vehicles, similar results are expected when modeling damaged vehicles. Of course, it is not always possible to fully capture the geometry of a damaged vehicle using eight photographs. However, when more photographs are required, the expected accuracy would be similar or better than that reported here, as additional photographs will ultimately improve the photogrammetric solution.

SUMMARY/CONCLUSIONS

1. Using retroreflective targets, a field-calibrated digital camera, an accurate scale bar, and sufficient mutual points between

photographs (such as those provided, in part, by the spheres discussed above), an accurate model of a vehicle can be generated photogrammetrically with eight photographs.

2. The average residual between corresponding photogrammetry and total station points in this study was 1.7 mm (N 258, SD = 0.8 mm) with a 95% confidence level of 3.1 mm.
3. The average residual between corresponding photogrammetry and FaroArm points in this study was 1.2 mm (N= 83, SD = 0.56 mm).
4. When using the vehicle modeling technique detailed here, a photogrammetry user can be 95% confident that the true position of a point will be within 2.1 mm of the location of the point obtained via photogrammetry.

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Documents

Document Sharing Hub

APPENDIX

APPENDIX A - PHOTOGRAPHS USED FOR ACURA PHOTOGRAMMETRY VS. TOTAL STATION MODEL



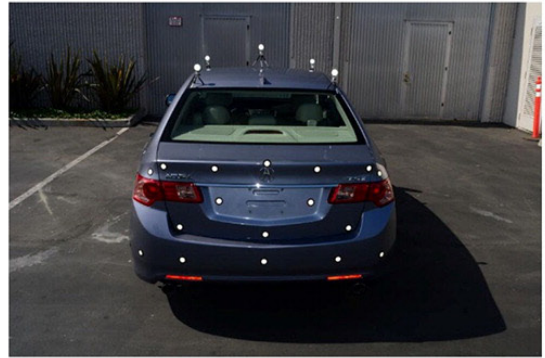
f/11, 1/160 s, ISO 200



f/11, 1/160 s, ISO 200



f/11, 1/125 s, ISO 200



f/11, 1/125 s, ISO 200



f/11, 1/160 s, ISO 400



f/11, 1/160 s, ISO 400



f/11, 1/160 s, ISO 400



f/11, 1/160 s, ISO 400