A Survey of Multi-View Photogrammetry Software for Documenting Vehicle Crush

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Toby Terpstra, Tilo Voitel, and Alireza Hashemian
Kineticorp LLC

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Abstract

Video and photo based photogrammetry software has many applications in the accident reconstruction community including documentation of vehicles and scene evidence. Photogrammetry software has developed in its ease of use, cost, and effectiveness in determining three dimensional data points from two dimensional photographs. Contemporary photogrammetry software packages offer an automated solution capable of generating dense point clouds with millions of 3D data points from multiple images. While alternative modern documentation methods exist, including LiDAR technologies such as 3D scanning, which provide the ability to collect millions of highly accurate points in just a few minutes, the appeal of automated photogrammetry software as a tool for collecting dimensional data is the minimal equipment, equipment costs and ease of use. This paper evaluates the accuracy and capabilities of four automated photogrammetry based software programs to accurately create 3D point clouds, by comparing the results to 3D scanning. Both a damaged and undamaged vehicle were documented with video and photographs and on average the damaged vehicle set returned more data points with higher accuracy than the undamaged vehicle set. Four cameras types were evaluated and more accurate results were achieved when using either a DSLR or a point-and-shoot camera than when using a GoPro, or a cell phone camera. Photogrammetry data from video footage was analyzed and found to be both less accurate and to return less data than photographs. By limiting the number of photographs used, it was found that a photogrammetry solution could be achieved with as few as 16 photographs encircling a vehicle, but better results were reached with a larger number of photographs.

Introduction

Photogrammetry has been previously validated as an effective technology for documenting both damaged vehicles and scenes [1,2,3,4,5,6,7,8,9,10,11,12]. Modern photogrammetry uses the same photogrammetric principles, but requires less user input and delivers more data points in its solution. Photogrammetry software is capable of generating point clouds similar to a 3D laser scanner. This technology is sometimes referred to as multi-view photogrammetry, automatic multi-image photogrammetry, [13] or photo-based 3D scanning [17]. For this paper, four automated photogrammetry software packages were chosen to evaluate the ability of collecting three-dimensional data from both damaged and undamaged vehicles. The point clouds resulting from the automated photogrammetry software contain hundreds of thousands and even millions of 3D data points. These point clouds were then compared to corresponding data collected using a 3D laser scanner. The four software titles chosen for this study are listed below.

1. PhotoModeler Scanner by EOS (version 2015.1.1)
2. PhotoScan by Agisoft (version 1.1.6)
3. Pix4Dmapper by Pix4D (version 2.0.83)
4. VisualSFM by Changchang Wu (version 2.6.2)

To analyze the software limitations related to camera type, four cameras were selected and photogrammetry point cloud solutions from each were compared. The cameras chosen for this study are listed below.

1. Canon EOS 5D Mark II
2. Canon PowerShot G16
3. GoPro Hero4 Black
4. Samsung Galaxy S6 Active

Photographs of damaged vehicles generally contain more unique and recognizable features such as dents, crumpled metal, scratches, abrasions, or a flaking of primer and paint. These present more unique features for the software to recognize than an exemplar or undamaged vehicle. To further understand if these features improve the photogrammetry solutions, both damaged and undamaged data sets are compared. Similarly, the photograph and video data sets are compared to understand their advantages and disadvantages.

Additionally, software limitations related to the number of photographs used the following data sets are created and evaluated for accuracy and number of returned 3D data points.

1. ~160 photographs
2. 80 photographs
3. 40 photographs
4. 16 photographs
5. 8 photographs

Dense photogrammetry point clouds were created within the software for all of the data sets. For the purposes of this paper these data sets will be referred to as photogrammetry point clouds. They were then independently scaled, aligned and evaluated to 3D scan data. For distinction and clarity, these will be referred to as LiDAR point clouds or LiDAR data.

Methodology

For this paper an accident or damaged 2013 Ford Taurus and an exemplar or undamaged 2014 Ford Taurus were analyzed. These vehicles were selected because they fall within the same sister year range (2010-2015) and were both white in color. When using a 3D scanner to document a vehicle, it is the authors' experience that lighter colored vehicles typically return more 3D data points or a denser point cloud than darker colored vehicles. The higher reflectivity of white paint made these vehicles suitable for generating a LiDAR point cloud to be used as a baseline for comparing the photogrammetry based point clouds to.

Automated multi-view 3D photogrammetry solutions do not have an inherent real world scale. To provide this real world scale within the data sets, reference tape markers were setup at 0, 10 and 20 feet distances along the length of the vehicle, with an additional reference tape marker at 10 feet along the width of the vehicle. Blue and yellow tape was used to insure high contrast and good visibility. These were placed on the ground alongside the vehicles so as to be visible in photographs and video passes (Figures 1 and 2). The markers were approximately 4 inches by 7 inches in length and were placed with the center of the yellow tape at the set distances using a tape measure. These reference tape markers were not moved during the photograph and video documentation process. They were visible within the resulting photogrammetry point clouds and were used to determine a scale factor for each individual set.

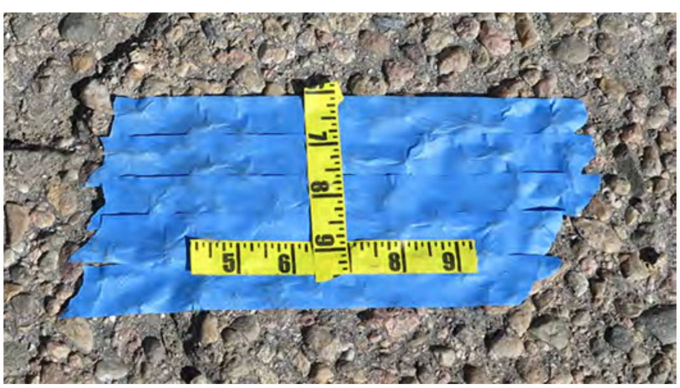

Figure 1. Blue and yellow reference tape marker.

Figure 2. Placement of reference markers at specific distances alongside the vehicles.

3D Scanner Documentation

The 3D Laser scanner used in this study for creating the LiDAR point clouds was a FARO Focus 3D X 330. The X 330 has a specified accuracy of ±2mm [15]. It is likely that all similar classed laser scanners on the market would have performed comparably. To achieve good overall coverage of the vehicles, two scans were completed at approximately 6.3 feet off of the ground, centered in front and behind the vehicle, and another four scans at approximately 3.4 feet above ground off of each corner of the vehicle, for a total of 6 scans per vehicle (Figure 3). The scans were 360° complete scans with settings of 1/5 for resolution and level 4 for quality. Each scan recorded approximately twelve million points and took approximately 8 minutes to complete Four different cameras were chosen for this study to evaluate software limitations based on image sensor size and resolution. The first is a Canon EOS 5 Mark II. The Mark II is a professional DSLR, full frame camera; meaning that the CMOS (complementary metal-oxide semiconductor) image sensor size has physical dimensions analogous to 35mm film. It also offers the largest resolution of the four at 21.1 Megapixels. The second camera is a Canon PowerShot G16. This camera falls within the "Point-and-shoot" category. It has the second largest image sensor, a BSI-CMOS sensor (Backside illuminated) and is much less expensive. The third camera is a GoPro Hero4 Black. This camera is capable of recording ultra HD video and was chosen for the study because of its popularity and versatility. GoPro cameras are very popular in action sports and UAV (Unmanned Aerial Vehicle) communities because of the size, durability and resolutions offered. The fourth camera is from a Samsung Galaxy S6 Active cell phone. This camera also has a BSICMOS sensor but has the smallest images sensor size in the study (Table 1).

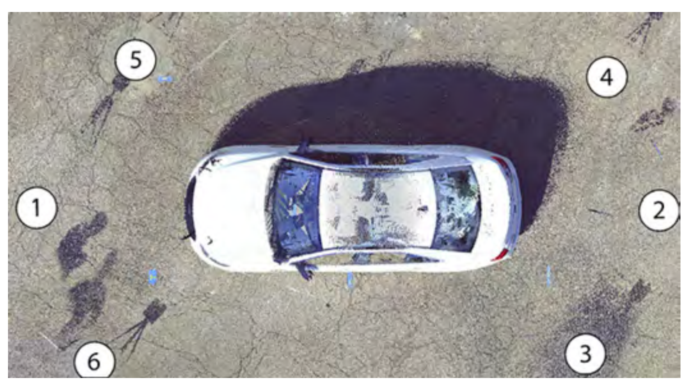

Figure 3. An orthographic top view of the resulting LiDAR point cloud. Numbers indicate 3D scanner placement for overall coverage of test vehicles.

Table 1. A comparison of cameras used in the study.

Camera	Resolution	Mega Pixels	Sensor Type	Sensor Size (mm)	Focal Length (35mm eq.)
Canon EOS 5D Mark II	5616 x 3744	21.1	CMOS	35.8 x 23.9	24 mm
Canon PowerShot G16	4000 x 2664	12.1	BSI-CMOS	7.44 x 5.58	29.7 mm
GoPro Hero4 Black	4000 x 3000	12	CMOS	6.17 x 4.55	15 mm
Samsung Galaxy S6 Active	5312 x 2988	16	BSI-CMOS	5.79 x 4.01	28 mm

Photograph and Video Documentation

Attention was given to the framing of the video as well as the photographs such that each photograph and frame of video would contain the entire vehicle without unnecessary amounts of the surrounding scene. The resulting imagery contains the reference tape markers setup alongside the vehicles. While the markers are not in every frame, they are contained within an adequate number of the complete photograph sets (~160 photographs) to allow for individual scaling of the resulting solution data using the markers within the data itself (Figure 4).

Figure 4. Example of vehicle framing within photographs and video.

Photograph sets were taken at two heights, the first being approximately 3.25 feet above ground and the second approximately 5.5 feet above ground to provide good overall coverage of the vehicle exterior (Figure 5).

Figure 5. Photographing the undamaged vehicle.

The vehicles were photographed walking around them at approximately 4.5° increments at both heights, resulting in approximately 80 photographs for each pass and approximately 160 photographs per camera, per vehicle. Tripods were not used in this process, however photograph locations were similar from camera to camera. Appendix A contains complete photo sets for each camera. Video passes were conducted with the Canon PowerShot G16 at similar heights walking around each vehicle. Each video pass was approximately 50 to 60 seconds in length equating to approximately 1650 frames at 30 frames per second (fps) for a total of approximately 3300 frames per vehicle (Figure 6).

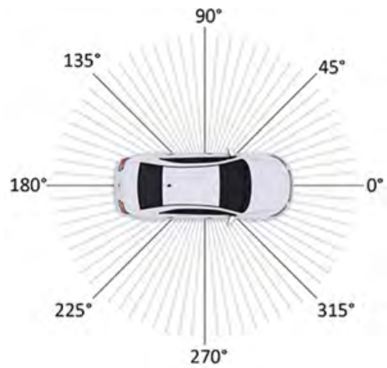

Figure 6. Incremental photographs taken at approximately 4.5° increments around the vehicles.

Photogrammetry Software

There are a number of close-range photogrammetry software titles available including some that require calibrated cameras, coded targets [10, 11] or manual correlated pixel selections in multiple photographs [3, 8]. These titles do not all return data in the form of a point cloud. Some titles are specifically designed to return discrete points chosen by the user and others automatically generate optimized 3D meshes from the solution. There also exist hardware photogrammetry solutions such as white light scanners that generate 3D data through the use of stereoscopic cameras and projected light patterns on a surface.

This study is of automated multi-view photogrammetry software that uses photographs or video frames and automatically solves for camera positions using similarities within the images, and then generates a 3D point cloud of data. There are also automated multiview photogrammetry software titles that generate a surfaced polygonal mesh rather than a point cloud. These were not chosen for the study because of the dissimilarity of their solution to 3D scan data. 3D scanning has become a widely accepted method for documenting vehicles and the resulting point cloud data is often used for taking measurements without need for processing into a surface or polygonal mesh.

The four software titles chosen for this study have a varying price range and include: VisualSFM, Agisoft Photoscan, EOS PhotoModeler Scanner, and Pix4Dmapper (Table 2).

Table 2. Software titles and cost as of November 2015.

Make	Title	Price
EOS	PhotoModeler Scanner	$2,500
Agisoft	PhotoScan	$179
Pix4D	Pix4Dmapper	$8,700
Changchang Wu	VisualSFM	NA

3D Scan Data Processing

The 3D scans collected from each vehicle were registered using the cloud to cloud registration method within FARO SCENE 5.4. The scan data of the scene and objects surrounding the subject vehicles was used in registration and then removed to create both a damaged vehicle point cloud and an undamaged vehicle point cloud. Default filtering levels were used within the software and additional errant points, such as a user standing in the scanning area, are easily visible when rotating around the cloud, and were removed. These data sets were then exported from FARO SCENE in the ".pts" file format.

Photogrammetric Data Processing

Lens distortion also needs to be considered when processing the photographs [16]. PhotoModeler Scanner works with calibrated cameras to remove lens distortion and has the option of manually calibrating a camera taking images of a grid at different angles [17]. Agisoft PhotoScan has an automatic method to solve for lens distortion [14, 18]. Pix4Dmapper looks to the EXIF data of photographs to find the camera make and model. If the lens profile is stored within the software database, it then automatically removes lens distortion from the photographs. Pix4Dmapper also estimates distortion processing during initial processing [19]. VisualSFM can solve for distortion automatically, but it supports only one radial parameter in their model. This may not work for all cameras and is listed under software limitations [20, 21].

For consistency, lens distortion was removed from each of the camera photograph and video sets prior to photogrammetry software processing. There are a number of other software titles for removing lens distortion, however DXO Viewpoint and Adobe Lens Profile Creator were used to remove lens distortion for this study (Table 3).

Table 3. Software used for lens distortion removal.

Camera	Software used to remove lens distortion
Canon EOS 5D Mark II	DXO Viewpoint 2.5.8
Canon PowerShot G16	DXO Viewpoint 2.5.8
GoPro Hero4 Black	DXO Viewpoint 2.5.8
Samsung Galaxy 6 Active	Adobe Lens Profile Creator 1.0.4

The photographs and video were then run through each software title using software recommended settings. The processing was performed in a similar manner for each software title and generally took between 1 and 5 hours, depending on the number of photos or frames in the data sets. After the processing was complete, the data sets were exported from the photogrammetry software. A ".pts" file was exported from PhotoModeler Scanner and a ".ply" file was exported from Agisoft PhotoScan, Pix4Dmapper, as well as VisualSFM (Figure 7), (Table 4).

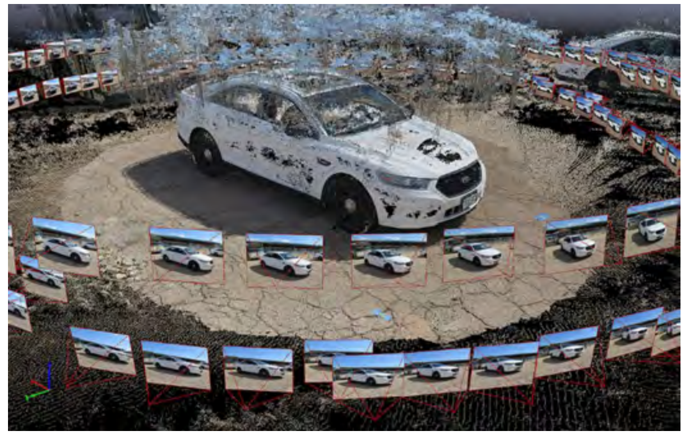

Figure 7. Photogrammetry point cloud solution with camera locations and photographs displayed. Canon PowerShot G16, 159 photographs processed in Pix4Dmapper.

Table 4. File formats available for export from each software title.

Software	Point cloud output file formats
PhotoModeler Scanner 2015.1.1	DXF, 3DS, WRL, OBJ, TXT, IGS, 3DM, STL, MA, KML, KMZ, MS, CSV, PTS, LAS, FBX
Agisoft PhotoScan 1.1.6	PLY, TXT, LAS, E57, U3D, PDF , OBJ, ZIP
Pix4Dmapper 2.0.83	LAS, LAZ, PLY, XYZ
VisualSFM 0.5.26	PLY

Scaling and Comparing the Point Clouds

The data sets were then individually imported into Cloud Compare, an open-source 3D point cloud software [22]. Upon import the photogrammetry data sets all had a different scale and orientation. In order to compare them to the LiDAR data sets, the photogrammetry data sets needed to both be scaled and aligned. Cloud Compare is a software package capable of importing, aligning and analyzing distances between two separate point clouds. Cloud Compare also has point to point measurement tools and the ability to multiply or scale entire point clouds. Both of these features were utilized in order to scale the software data sets. First a measurement was taken between the twenty foot blue and yellow tape markers (Figure 1, 7). This distance was then used to determine a scale factor for the set. After scaling the entire set by this factor, a second measurement was taken to ensure accurate scaling and to evaluate, at some level, the possible error associated with the manual selection of scaling points. Refer to Table 5 for a summary.

The overall accuracy of scaling the photogrammetry point cloud sets is dependent on several factors. These include the accuracy of the software data points at the tape marker locations, the number of points available for selection, the clarity of points such that the center of the tape can be visually determined, as well as the manual and subjective determination of what points are chosen as a basis for scaling the data set (Figure 8).

Table 5. Percent error in manual point selection before and after scaling. (Canon G16, entire photo sets of the undamaged (EXEM) and damaged (ACC) vehicles)

SOFTWARE	ACC/ EXEM	1ST MEAS.	SCALE FACT.	2ND MEAS.	DIFF	AVE. % ERROR
PhotoModeler	EXEM	9.29	25.83	239.97	0.03	0.02%
PhotoModeler	ACC	8.39	28.61	240.06	0.06	
PhotoScan	EXEM	5.35	44.87	239.96	0.04	0.02%
PhotoScan	ACC	20.25	11.85	239.94	0.06	
Pix4Dmapper	EXEM	110.00	2.18	239.97	0.03	0.02%
Pix4Dmapper	ACC	101.11	2.37	240.06	0.06	
VisualSFM	EXEM	7.45	32.2	240	0.0	0.00%
VisualSFM	ACC	13.69	17.54	240	0.0	

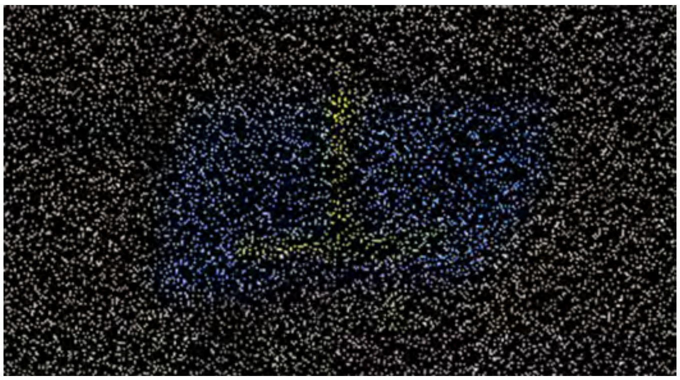

Figure 8. Photogrammetry point cloud of tape marker (Pix4Dmapper, Canon G16, entire photo set).

After scaling, the photogrammetry point cloud solutions were aligned to the LiDAR point clouds using Cloud Compare. This was accomplished using three or more common points. Recognizing that a poorly aligned dataset could produce inaccurate results during comparison, each alignment was analyzed for accuracy visually and quantitatively. Cloud Compare calculates a root mean square (RMS) value based on the alignment points chosen. When a larger number was reported by the software, additional points were chosen in effort to decrease this value and achieve a more accurate result. The alignments were visually inspected by toggling on and off the other data set from multiple vantages to see if a visual shift occurred. If the datasets appeared to visually be offset in translation or rotation, additional or alternate alignment points were chosen.

Improper scaling of the point cloud affects alignment and overall accuracy. To illustrate this concept, a properly scaled photogrammetry data set was intentionally scaled again by a factor of 1.01, and a new alignment was attempted between the LiDAR data set and the photogrammetry set. The calculated alignment RMS (.92") between the improperly scaled data set to the LiDAR data was approximately 8 times greater than the RMS (.11) calculated with the properly scaled photogrammetry data set. Figure 9 illustrates this by showing both the properly scaled photogrammetry point cloud (top) and the improperly scaled point cloud (bottom). The coloring of the photogrammetry based point clouds in Figure 9 is based on point distance away from the LiDAR data. Note how the improperly scaled data set has a different coloring. The overall length of this vehicle being greater than the width makes the improper scaling more visually apparent on the front and back of the vehicle. In a similar way, if the data was scaled appropriately but not aligned well, these color differences would be apparent more in one area of the vehicle than another.

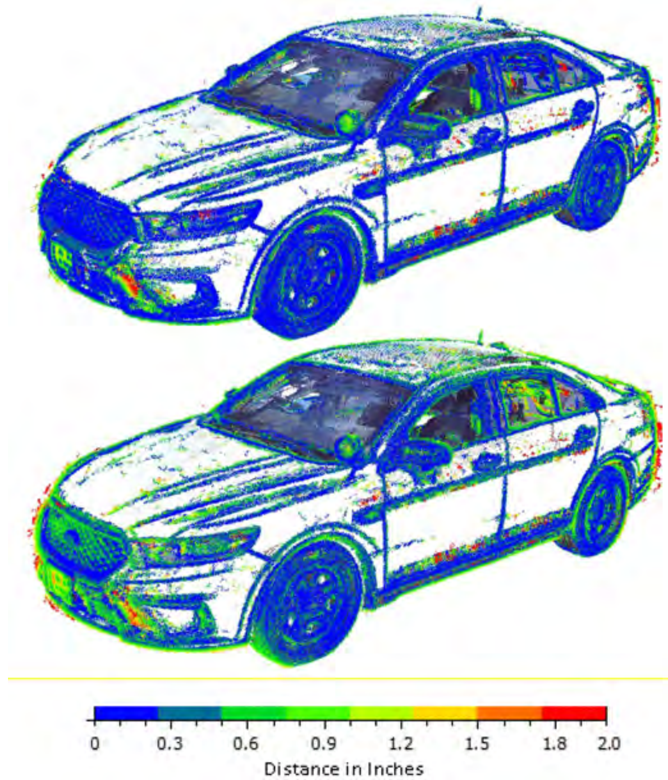

Figure 9. Undamaged vehicle LiDAR point clouds overlaid with photogrammetry point clouds. The LiDAR point clouds have typical photo coloring and the photogrammetry point clouds are colorized to represent point distance away from the LiDAR data. The photogrammetry point clouds on top vehicle are properly scaled and aligned. The photogrammetry point clouds on the bottom were scaled by a factor of 1.01.

Once a good alignment was achieved, the photogrammetry based point cloud was manually filtered in a similar manner to that of the scan data or LiDAR processing. This was done manually by removing noticeably errant points or islands of data points from the point cloud. In instances where the resulting data appeared to contain noticeably errant points, but no clear line could be determined for separating the errant points, no points were removed from the data set. These points could be considered more of a peninsula than an island. CloudCompare (v. 2.6.2) has a filtering option called ‘SOR’ or Statistical Outlier Removal. This filter was run on all photogrammetry data sets with default software values of ‘10’ for the number of points used in mean distance estimation and ‘1.00’ for the standard deviation multiplier threshold. Additionally, because 3D scanners are known to have difficulty in returning accurate data on and through windows, and because these points are generally not the focus of exterior vehicle documentation, points in the area of the windows and vehicle interior were removed from the photogrammetry based data sets (Figure 10).

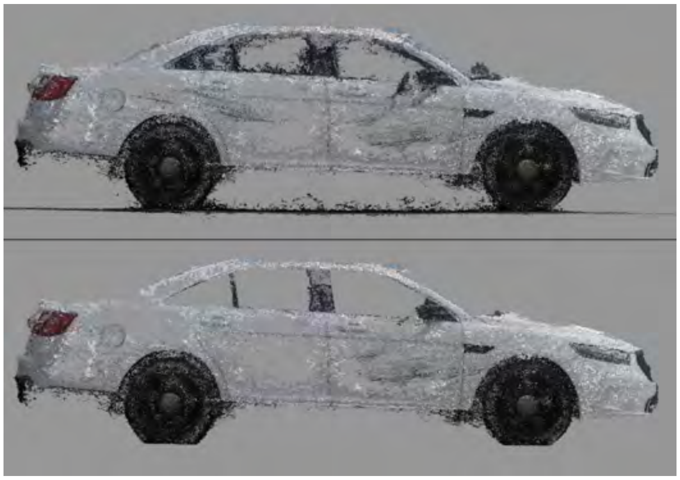

Figure 10. Photogrammetry point clouds before and after filtering out the ground under vehicle, isolated point groups, windows and interior. (PhotoScan, undamaged vehicle, Samsung Galaxy 6 Active, entire photo set).

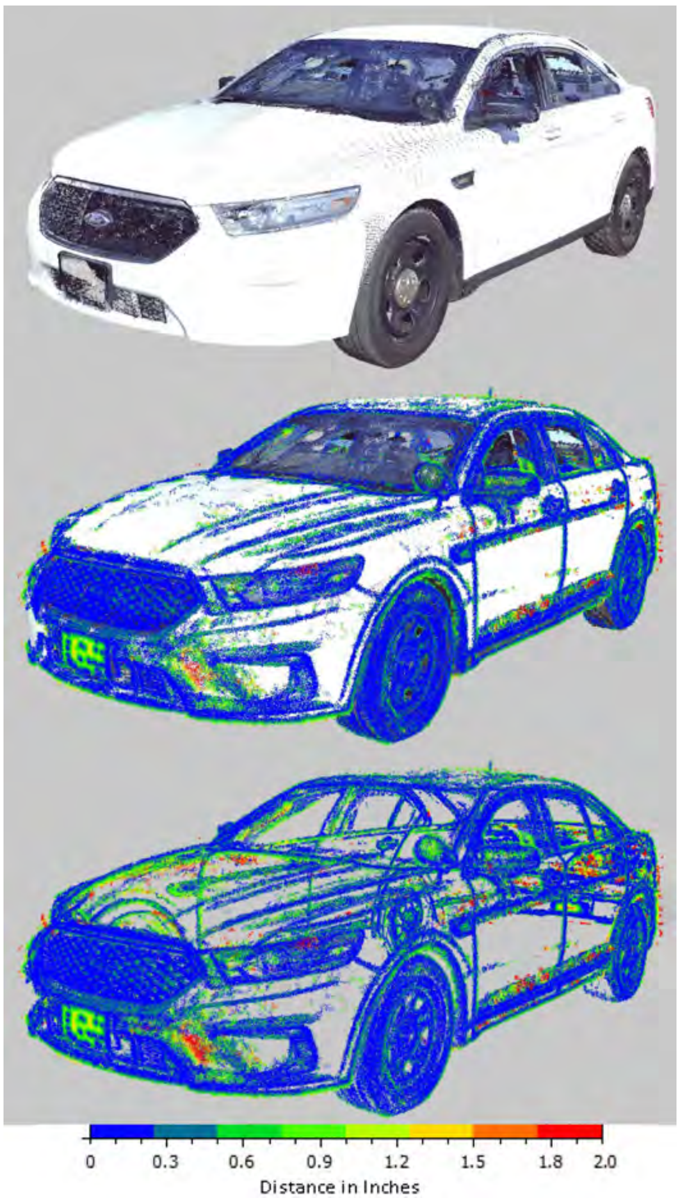

Figure 11. Undamaged vehicle point clouds. Top: LiDAR point cloud. Middle: LiDAR point cloud with photogrammetry point cloud aligned. Bottom: Photogrammetry point cloud with the same distance based colorization. (PhotoModeler Scanner, Canon G16, entire photo set).

This was done to prevent the comparison of photogrammetry based points to possible errant LiDAR points. A comparison of the potential for these window and vehicle points to effect data comparisons was done for one data set. The Canon G16, 160 photo set of the damaged vehicle was processed in PhotoModeler prior to removal and again after removing these points. The data set after point removal was found to be approximately 3% more accurate at all distances in the analysis. Because point distribution in these areas was similar in all the photogrammetry point clouds, it is likely that a similar percent of increase in accuracy was achieved by removal of these points in all of the photogrammetry point clouds.

The photogrammetry point clouds were then individually compared to the LiDAR data sets within Cloud Compare. The "Compute cloud/cloud distance" tool was used, which calculates distances from one data set to the other based on the nearest neighbor. The results were separated into nine data sets for each point cloud, points found to be within 0 to .25 inches, 0 to.25 inches, 0 to .5 inches, 0 to .75 inches, 0 to 1 inch, 0 to 1.25 inches, 0 to 1.5 inches, 0 to 1.75 inches, 0 to 2 inches, and points equal to or greater than 2 inches (Figure 11).

Results

The total number of LiDAR points used for comparison from the undamaged vehicle scan was 2,964,140. The total number of points for the damaged vehicle scan was 2,621,805. These LiDAR points were used as a baseline for all of the point cloud analyses (Table 6).

Initial Software Evaluation

The entire Canon G16 photo sets for both the undamaged vehicle (159 photos) and the damaged vehicle (157 photos) were run through each of the four photogrammetry software titles. After filtering, as described in the photogrammetric data processing section, PhotoModeler Scanner returned an average of 1,306,089 vehicle comparison data points. PhotoScan returned 1,887,418, Pix4Dmapper returned 1,562,414 and VisualSFM returned 645,013 comparison points (Table 6).

Table 6. Canon G16 full photo sets with number of comparison points for damaged and undamaged vehicle sets.

Make	Photogrammetry Software	Undamaged Vehicle	Damaged Vehicle	Compariso n Points
EOS	PhotoModeler Scanner	X		1,384,383
			X	1,227,795
Agisoft	PhotoScan	X		1,742,939
			X	2,032,022
Pix4D	Pix4Dmapper	X		1,648,009
			X	1,476,818
Changchang Wu	VisualSFM	X		641,062
			X	648,964
Make	**LiDAR Scan**			**Compariso n Points**
FARO	Focus 3D X 330	X		2,964,140
			X	2,621,805

Distances were then evaluated between the photogrammetry point clouds and the LiDAR point clouds. The photogrammetry point clouds were found to have an average of 59% of their points within .25 inches of the LiDAR data, with a standard deviation of 4%. An average of 82% of the points were located within .5 inches with a standard deviation of 3%. An average of 90% of the points were located within .75 inches, with a standard deviation of 2%. An average of 94% of the points were located within 1 inch, with a standard deviation of 2%. An average of 96% of the points were located within 1.25 inches, with a standard deviation of 1%. An average of 97% of the points were located within 1.5 inches, with a standard deviation of 1%. An average of 98% of the points were located within 1.75 inches, with a standard deviation of 1%. (Table 7, Figures 12, 13, and 14). Appendix B contains data distribution histograms for each of the software data sets.

Table 7. Canon G16 full photo sets: Percentage of points within specific distances, average and standard deviation within specific distances of the LiDAR points. ("Exem" for undamaged and "Acc" for damaged)

Photogrammetry Software	.25"	.50"	.75"	1.0"	1.25"	1.5"	1.75"	2.0"
PhotoModeler-EXEM	53%	81%	91%	95%	97%	98%	99%	99%
PhotoModeler-ACC	57%	82%	92%	96%	98%	98%	99%	99%
PhotoScan-EXEM	58%	80%	88%	92%	94%	96%	97%	98%
PhotoScan-ACC	66%	86%	92%	94%	96%	97%	97%	98%
Pix4Dmapper-EXEM	59%	80%	88%	93%	95%	97%	97%	98%
Pix4Dmapper-ACC	54%	78%	88%	92%	94%	96%	97%	97%
VisualSFM-EXEM	57%	80%	88%	92%	94%	96%	97%	98%
VisualSFM-ACC	63%	86%	93%	96%	97%	98%	98%	99%
Average	59%	82%	90%	94%	96%	97%	98%	98%
Standard Deviation	4%	3%	2%	2%	1%	1%	1%	1%

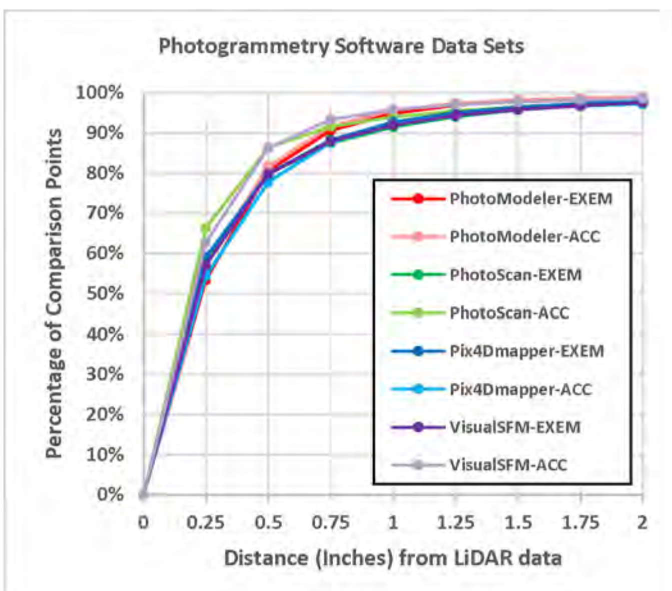

Figure 12. A cumulative probability plot of data from Table 7 with percentage of points over specific distances.

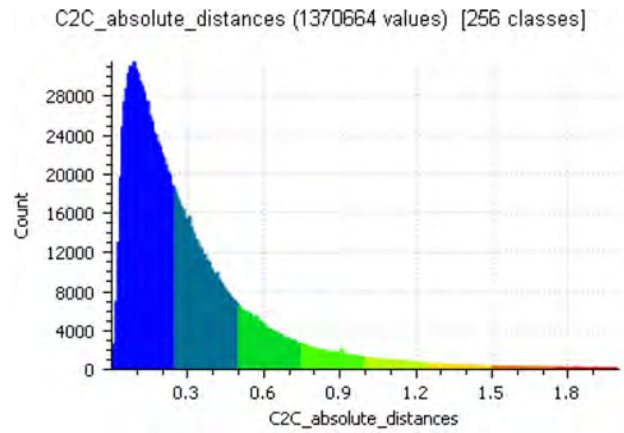

Figure 13. A histogram of the first row of data in Table 7. The colorization is based on .25 inch increments. 13,719 or approximately 1% of the points were at a distance greater than 2 inches, with a maximum distance of 14.6 inches. For clarity this is the PhotoModeler Scanner, Canon G16, undamaged vehicle, entire photo set. Appendix B contains similar histogram data for all rows within Table 7.

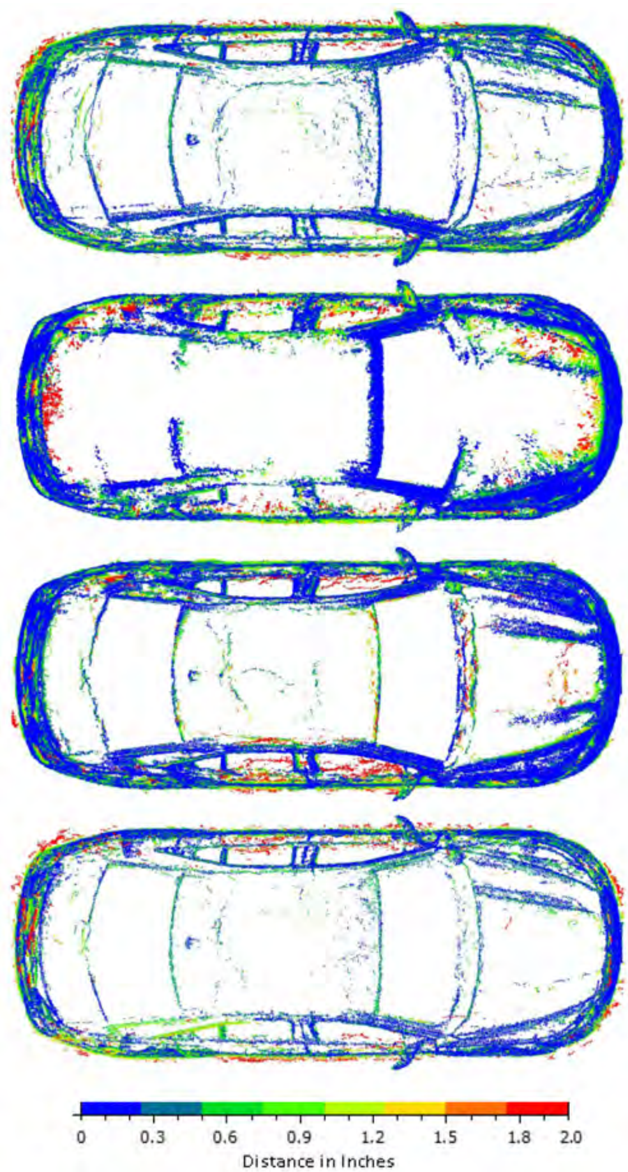

Figure 14. An orthographic top view of the photogrammetry software based point clouds taken with the Canon G16, full photograph set. In order from top to bottom: PhotoModeler Scanner, PhotoScan, Pix4Dmapper, and VisualSFM. Colorization is based on distance from LiDAR data.

A pattern appears visually within the data such that the photogrammetry points located closer to the LiDAR points are concentrated around areas with more contrast within the photos. For instance, there are more photogrammetry points, within the 0 to .25" range, near body panel seams and edges of geometry (Figure 15). Where the software has limited unique values or higher contrast between adjacent pixels, greater inaccuracies exist and there are limited resulting points. This is most visible in the center of larger vehicle body panels, such as the middle of the driver's door.

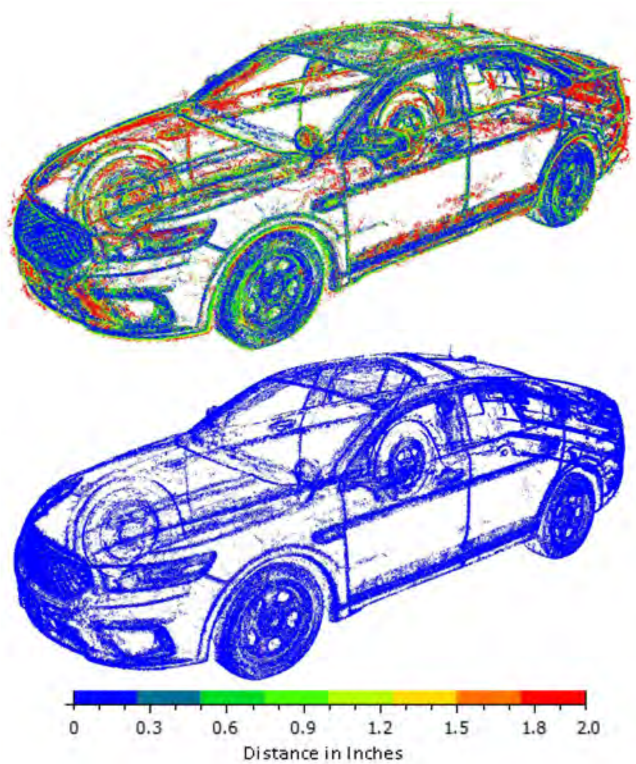

Figure 15. PhotoModeler Scanner, Canon G16, undamaged vehicle, entire photo set. The top vehicle shows photogrammetry data at all distances from the LiDAR point cloud. The bottom vehicle shows only points located within .25 inches of the LiDAR data. Colorization is based on distance from LiDAR data.

Camera Comparison

The four cameras used in the study were individually evaluated using Agisoft PhotoScan. PhotoScan had similar results to other photogrammetry software in the initial evaluation and was chosen because it returned the highest number of data points and it had the highest average percentage of points returned between 0 and .25" for both the damaged and undamaged data sets. While the other software titles were not evaluated for all of the cameras, based on the results from the initial software comparison, it is likely that they would have similar results.

The entire photo set for each camera (Table 8), was processed through PhotoScan. After filtering, as described in the photogrammetric data processing section, the Canon 5D Mark II had an average of 3,502,111 vehicle comparison points. The Canon PowerShot G16 returned an average of 1,887,481. The GoPro Hero4 Black returned an average of 1,290,616 vehicle comparison points, and the Samsung Galaxy S6 Active returned an average of 2,766,352 comparison points (Table 9).

Table 8. Total number of photos taken with each camera for undamaged and damaged vehicles.

Make	Model	Undamaged	Damaged
Canon	EOS 5D Mark II	157	162
Canon	PowerShot G16	159	157
GoPro	Hero4 Black	161	163
Samsung	Galaxy S6 Active	162	178
	Average	160	165

Table 9. Number of comparison points from Agisoft PhotoScan per camera.

Make	Model	Undamaged Vehicle	Damaged Vehicle	Comparison Points
Canon	EOS 5D Mark II	X		2,053,297
			X	4,950,925
Canon	PowerShot G16	X		1,742,939
			X	2,032,022
GoPro	Hero4 Black	X		940,082
			X	1,641,149
Samsung	Galaxy S6 Active	X		2,128,764
			X	3,403,940

Distances were then evaluated between the photogrammetry point clouds and the LiDAR point clouds. The photogrammetry point clouds were found to have an average of 55% of their points within .25 inches of the LiDAR data, with a standard deviation of 8%. An average of 77% of the points were located within .5 inches with a standard deviation of 8%. An average of 85% of the points were located within .75 inches, with a standard deviation of 7%. An average of 89% of the points were located within 1 inch, with a standard deviation of 6%. An average of 92% of the points were located within 1.25 inches, with a standard deviation of 4%. An average of 94% of the points were located within 1.5 inches, with a standard deviation of 4%. An average of 95% of the points were located within 1.75 inches, with a standard deviation of 4%. An average of 96% of the points were locates within 2 inches of the LiDAR data, with a standard deviation of 3%. (Table 10, Figures 16 and 17).

Table 10. Full photo sets for each camera processed in Agisoft PhotoScan. Percentage of points, average and standard deviation within specific distances of the LiDAR points. ("Exem" for undamaged and "Acc" for damaged)

Camera-Vehicle	.25"	.50"	.75"	1.0"	1.25"	1.5"	1.75"	2.0"
Canon Mark II-EXEM	59%	81%	89%	93%	95%	96%	97%	98%
Canon Mark II-ACC	60%	85%	92%	95%	97%	98%	98%	98%
Canon G16-EXEM	58%	80%	88%	92%	94%	96%	97%	98%
Canon G16-ACC	66%	86%	92%	94%	96%	97%	97%	98%
GoPro-EXEM	48%	68%	75%	80%	83%	85%	87%	89%
GoPro-ACC	53%	77%	85%	89%	92%	94%	95%	96%
Samsung-EXEM	42%	63%	74%	81%	85%	88%	91%	92%
Samsung-ACC	54%	77%	86%	91%	94%	95%	96%	97%
Average	55%	77%	85%	89%	92%	94%	95%	96%
Standard Deviation	8%	8%	7%	6%	5%	4%	4%	3%

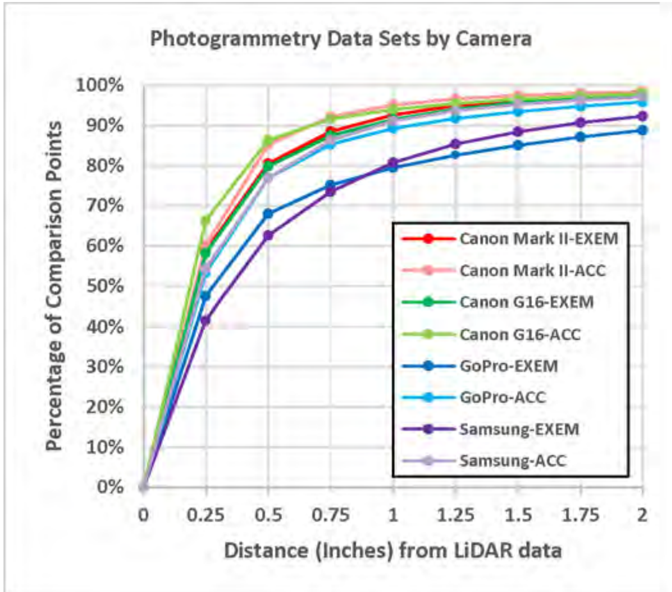

Figure 16. A cumulative probability plot of data from Table 10 with percentage of points over specific distances.

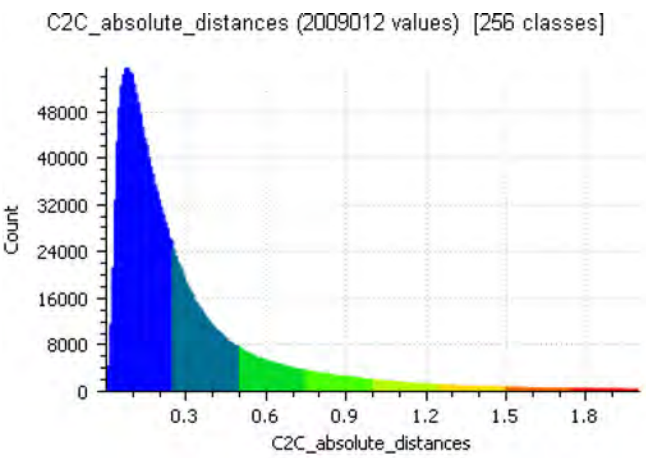

Figure 17. A histogram of the first row of data in Table 10. The colorization is based on .25 inch increments. 43,194 or approximately 2.2% of the points were at a distance greater than 2 inches, with a maximum distance of 7.7 inches. For clarity this is the Canon Mark II undamaged vehicle, entire photo set. Appendix C contains similar histogram data for all rows within Table 10.

Photographs and Video Comparison

Each of the 4 photogrammetry software titles is capable of using either photographs or frames from video. Video frame rates make it much quicker to obtain a large number of images (video frames) than taking photographs. To compare the quality of resulting photogrammetry point clouds from both photographs and video, a single camera, the canon PowerShot G16 was chosen. The G16 was chosen because it is was a relatively inexpensive point and shoot camera. Approximately 50 seconds of video was recorded of the undamaged vehicle and approximately 55 seconds of the damaged vehicle at 29.97 frames per second (fps). This equates to an average of more than 1,500 frames per vehicle. Because this is such a large number of images for the software to process, every 4th frame was chosen for a total of 403 frames for the undamaged vehicle and 389 frames for the damaged vehicle. These frames were then run through each of the software titles and the resulting photogrammetry point clouds were compared to the LiDAR point clouds. After filtering, PhotoScan returned an average of 500,821 vehicle comparison data points. Pix4Dmapper returned 509,559 and VisualSFM returned 170,026 vehicle comparison points. PhotoModeler was unable to process either the undamaged or damaged vehicle data set. This may have to do with computer hardware limitations, software limitations or a combination of both. (Table 11).

Table 11. Number of comparison points from the Canon PowerShot G16 video for damaged and undamaged vehicle sets.

Make	Photogrammetry Software	Undamaged Vehicle	Damaged Vehicle	Comparison Points
EOS	PhotoModeler Scanner	X		NA
			X	NA
Agisoft	PhotoScan	X		612,318
			X	389,323
Pix4D	Pix4Dmapper	X		588,256
			X	430,862
Changchang Wu	VisualSFM	X		177,038
			X	163,014

Distances were evaluated between the video photogrammetry point clouds and the LiDAR point clouds. The photogrammetry point clouds were found to have an average of 38% of their points within .25 inches of the LiDAR data, with a standard deviation of 5%. An average of 63% of the points were located within .5 inches with a standard deviation of 5%. An average of 76% of the points were located within .75 inches, with a standard deviation of 5%. An average of 84% of the points were located with 1 inch, with a standard deviation of 5%. An average of 88% of the photogrammetry points were located within 1.25 inches, with a standard deviation of 4%. An average of 91% of the points were located within 1.5 inches with a standard deviation of 3%. An average of 93% of the points were located within 1.75 inches, with a standard deviation of 2%. An average of 94% of the video photogrammetry points were located within 2 inches, with a standard deviation of 2%. (Table 12, Figures 18, and 19).

Table 12. Canon G16 video frames processed through the chosen photogrammetry software titles. Percentage of points, average and standard deviation within specific distances of the LiDAR points. ("Exem" for undamaged and "Acc" for damaged)

Photogrammetry Software	.25"	.50"	.75"	1.0"	1.25"	1.5"	1.75"	2.0"
PhotoModeler-EXEM	NA	NA	NA	NA	NA	NA	NA	NA
PhotoModeler-ACC	NA	NA	NA	NA	NA	NA	NA	NA
PhotoScan-EXEM	32%	59%	73%	81%	86%	89%	92%	94%
PhotoScan-ACC	33%	55%	67%	75%	81%	85%	88%	91%
Pix4Dmapper-EXEM	44%	67%	78%	85%	89%	91%	93%	95%
Pix4Dmapper-ACC	42%	68%	80%	87%	90%	93%	95%	96%
VisualSFM-EXEM	42%	68%	80%	86%	90%	92%	93%	94%
VisualSFM-ACC	36%	64%	80%	87%	91%	93%	95%	96%
Average	38%	63%	76%	84%	88%	91%	93%	94%
Standard Deviation	5%	5%	5%	5%	4%	3%	2%	2%

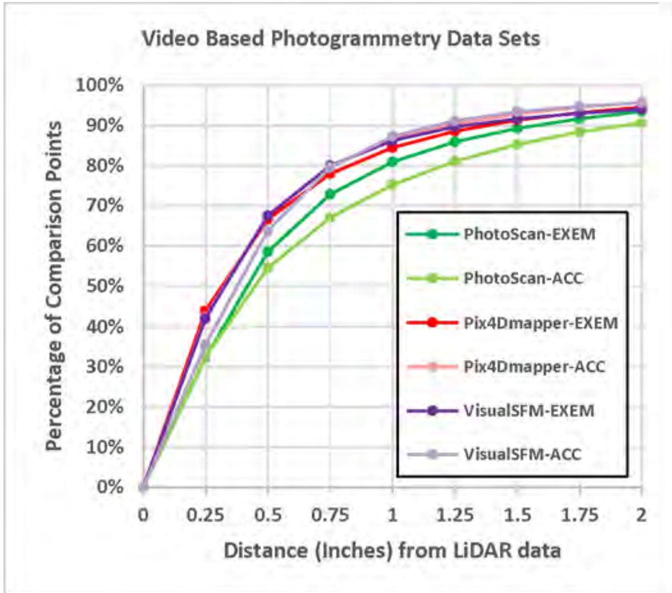

Figure 18. A cumulative probability plot of data from Table 12 with percentage of points over specific distances.

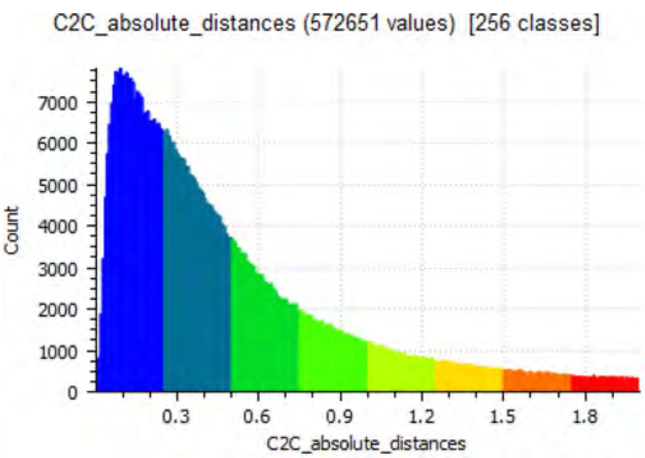

Figure 19. A histogram of the third row of data in Table 10 (Canon PowerShot G16, video set, undamaged vehicle, Agisoft PhotoScan). The colorization is based on .25 inch increments. A total of 39,667 or approximately 6.9% of the points were at a distance greater than 2 inches, with a maximum distance of 16.9 inches. Appendix D contains similar histogram data for all rows within Table 12.

Software Evaluation Using Limited Photographs

To understand software limitations related to the number of photographs, the Canon PowerShot G16 camera and Agisoft PhotoScan were chosen. New photograph sets were created from the original sets by limiting the number of photographs from ~160 to 80, 40, 16 and 8. After processing through the photogrammetry software, the sets were individually scaled based on the reference tape markers within the data sets, aligned, filtered and compared to the LiDAR point clouds.

The photogrammetry point clouds for the undamaged 159 photo set and damaged 157 photo set had an average of 1,887,481 points. The 80 photograph point cloud sets had an average of 1,160,870 points. The 40 photograph point cloud sets had an average of 911,671 points. The 16 photograph damaged point cloud set was unable to be processed, but the undamaged point cloud returned 77,928 points. Similarly no software solution was possible with the 8 photograph sets (Table 13).

Table 13. Comparison points for sets with varying amounts of photographs. Photographs taken with the Canon PowerShot G16, frames processed through Agisoft PhotoScan.

Photo Set	Undamaged Vehicle	Damaged Vehicle	Comparison Points
159	X		1,742,939
157		X	2,032,022
80	X		1,095,088
		X	1,226,652
40	X		817,612
		X	1,005,730
16	X		77,928
		X	NA
8	X		NA
		X	NA

Table 14. Varying amounts of photographs from the Canon PowerShot G16, processed through Agisoft PhotoScan. Percentage of points, average and standard deviation within specific distances of the LiDAR points.

Photo Set	.25"	.50"	.75"	1.0"	1.25"	1.5"	1.75"	2.0"
159-Photos-Exem	58%	80%	88%	92%	94%	96%	97%	98%
157-Photos-Acc	66%	86%	92%	94%	96%	97%	97%	98%
80-Photos-Exem	61%	84%	91%	95%	97%	98%	98%	99%
80-Photos-Acc	57%	83%	91%	94%	96%	97%	98%	98%
40-Photos-Exem	39%	63%	76%	85%	90%	93%	95%	97%
40-Photos-Acc	43%	70%	83%	90%	93%	96%	97%	97%
16-Photos-Exem	52%	79%	90%	93%	95%	96%	97%	97%
16-Photos-Acc	NA	NA	NA	NA	NA	NA	NA	NA
8-Photos-Exem	NA	NA	NA	NA	NA	NA	NA	NA
8-Photos-Acc	NA	NA	NA	NA	NA	NA	NA	NA
Average	54%	78%	87%	92%	94%	96%	97%	98%
Standard Deviation	9%	8%	5%	3%	2%	1%	1%	1%

Distances were evaluated between the photogrammetry point clouds and the LiDAR point clouds. The photogrammetry point clouds from ~160 photographs were found to have an average of 62% of their points within .25 inches of the LiDAR data. An average of 83% of the points were located within .5 inches. An average of 90% of the points were located within .75 inches. An average of 93% of the points were located within 1 inch. An average of 95% of the points were located within 1.25 inches. An average of 96% of the points were located within 1.5 inches. An average of 97% of the points were located within 1.75%, and an average of 98% of the points were located within 2 inches of the LiDAR data.

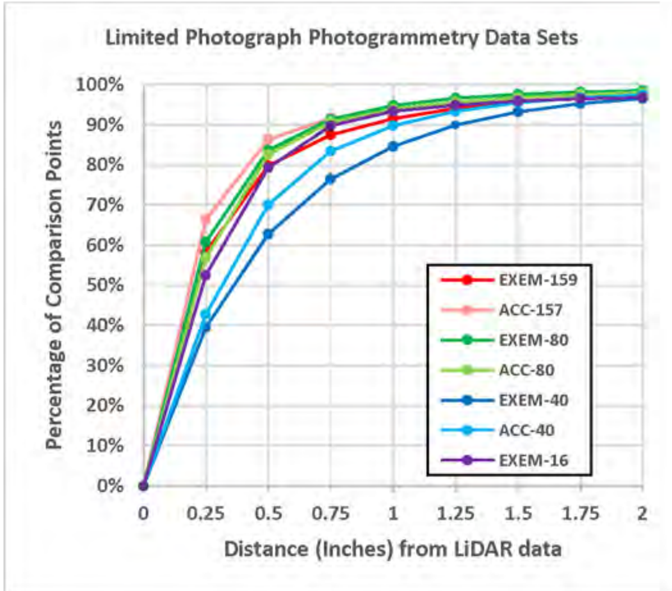

Figure 20. A cumulative probability plot of data from Table 14 with percentage of points over specific distances.

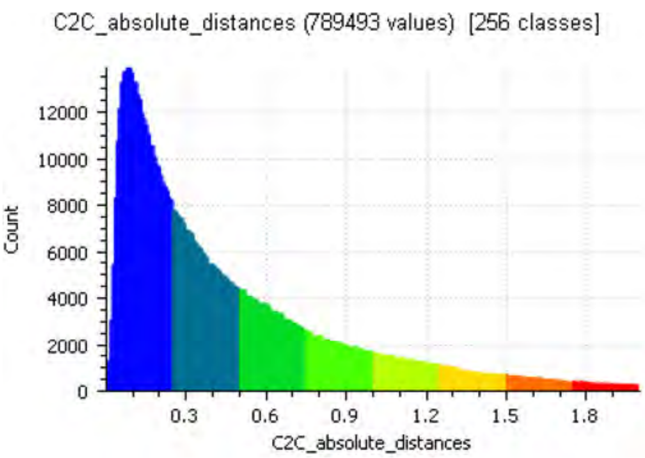

Figure 21. A histogram of the fifth row of data in Table 14 (Canon PowerShot G16, 40 photos, undamaged vehicle, Agisoft PhotoScan). The colorization is based on .25 inch increments. A total of 27,938 or approximately 3.5% of the points were at a distance greater than 2 inches, with a maximum distance of 9.8 inches. Appendix E contains similar histogram data for all rows within Table 12.

The photogrammetry point clouds from 80 photographs were found to have an average of 59% of their points within .25 inches of the LiDAR data. An average of 83% of the points were located within .5 inches. An average of 91% of the points were located within .75 inches. An average of 94% of the points were located within 1 inch. An average of 96% of the points were located within 1.25 inches. An average of 97% of the points were located within 1.5 inches. An average of 98% of the points were located within 1.75 and 2 inches of the LiDAR data.

The photogrammetry point clouds from 40 photographs were found to have an average of 41% of their points within .25 inches of the LiDAR data. An average of 66% of the points were located within .5 inches. An average of 80% of the points were located within .75 inches. An average of 87% of the points were located within 1 inch. An average of 92% of the points were located within 1.25 inches. An average of 94% of the points were located within 1.5 inches. An average of 96% of the points were located within 1.75 inches and an average of 97% of the points located within 2 inches of the LiDAR data.

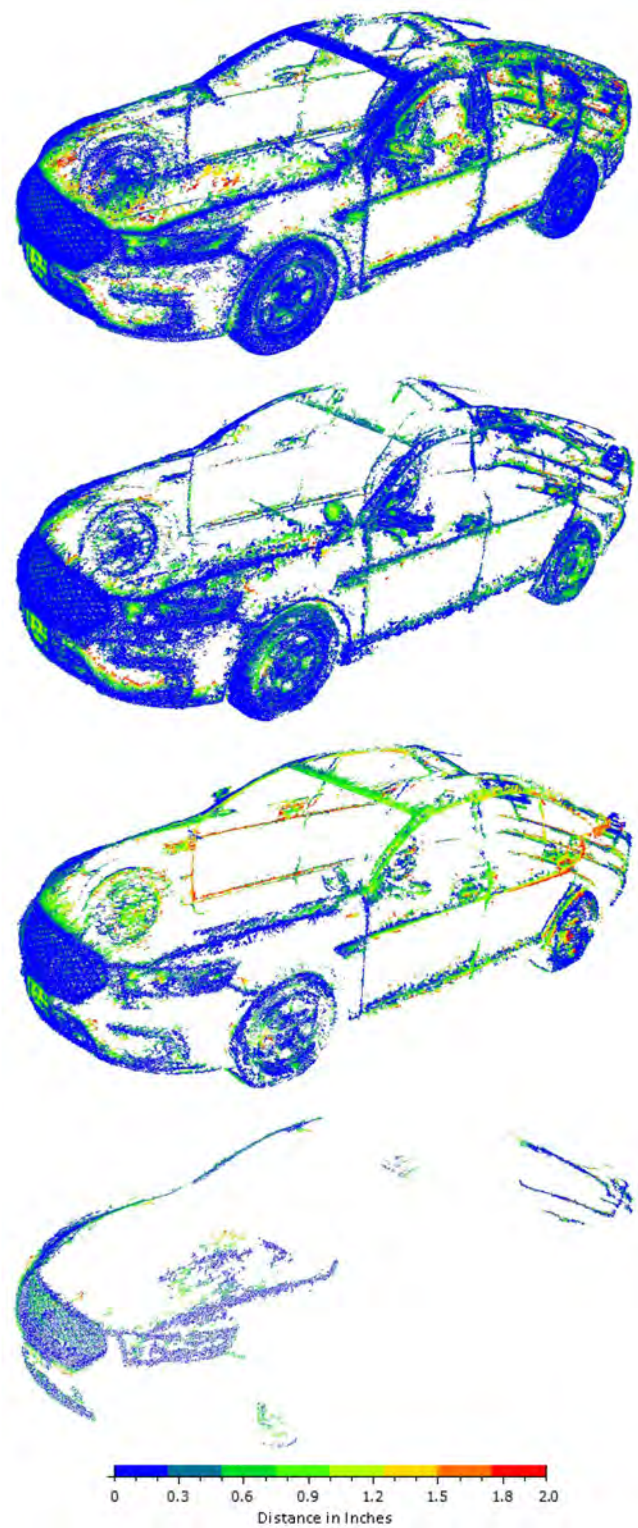

Figure 22. Exemplar vehicle photogrammetry data from Agisoft PhotoScan, Canon PowerShot G16. Top to bottom: 159 photo set, 80 photo set, 40 photo set, and 16 photo set. Colorization is representative of distance from LiDAR data. (Points beyond 2” are not shown)

For the 16 photograph sets, only the undamaged set was able to be processed in PhotoScan. It was found to have of 52% of the points within .25 inches of the LiDAR data, 79 % of the points within .5 inches, 90% of the points within .75 inches, 93% of the points within 1 inch, 95% of the points within 1.25 inches, 96% of the points within 1.5 inches, and 97% of the points within 1.75 and 2 inches of the LiDAR data. (Table 14, Figures 20, 21, and 22).

Damaged and Undamaged Vehicle Comparison

Damaged vehicles can contain dents, crumpled metal, missing components, scratches, abrasions or a flaking of primer and paint, whereby presenting more unique features for the software to recognize than an exemplar or undamaged vehicle. In order to understand if these features show advantages for the software, all of the photographs from the initial software testing section, taken by the Canon PowerShot G16 were processed through each of the 4 software titles and analyzed by undamaged and damaged vehicle groupings.

The average number of points returned from all software titles for the undamaged vehicle was 1,354,098. The average for the damaged vehicle was 1,346,400. The difference between the two averages is just 7,698 points. This difference is small and was not consistent across all data sets (Table 6). The damaged vehicle data sets did show an increase in accuracy for points when compared to the LiDAR data set. A visual comparison of damaged areas also shows that more points within .25 inches of the LiDAR data could be seen in body panels where damage was present than in those without damage. This is evident where greater areas of blue colored points (points within .25 inches of the LiDAR data) are visible in the damaged areas (Figure 23).

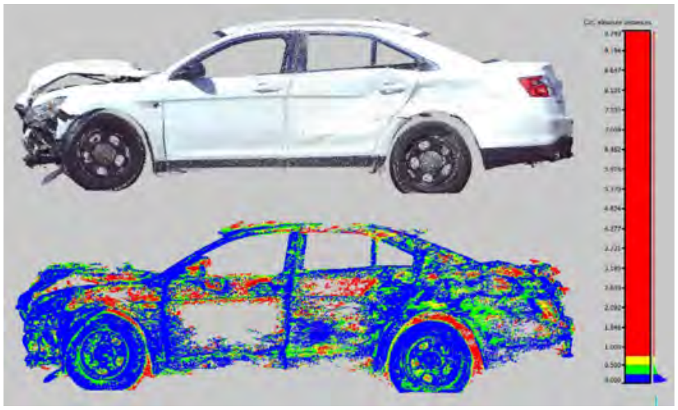

Figure 23. Areas of damage such as the driver's side rear door and the driver's side quarter panel exhibit more accurate data points than body panels that do not, such as the middle of the driver's door. The top vehicle with standard coloring is the LiDAR point cloud and the bottom vehicle is the photogrammetry point cloud. The colorization is based on distance with 0 to .25 inches shown in blue, .25 to .5 inches shown in green, .5 to .75 inches shown in yellow and .75+ inches shown in red (PhotoScan, Canon G16, damaged vehicle, entire photo set).

The average percentage of points located within specific distances from the LiDAR point clouds was also calculated. The undamaged photogrammetry point clouds had an average of 57% of their data points located within .25 inches of the LiDAR data, while the damaged photogrammetry point clouds had an average of 60% at the same distance. The undamaged photogrammetry point clouds had an average of 80% of their data points located within .5 inches of the LiDAR data, while the damaged photogrammetry point clouds had an average of 83%. The undamaged photogrammetry point clouds had an average of 89% of their data points located within .75 inches of the LiDAR data, while the damaged photogrammetry point clouds had an average of 91%. The undamaged photogrammetry point clouds had an average of 93% of their data points located within 1 inch of the LiDAR data, while the damaged photogrammetry point clouds had an average of 94%. The undamaged photogrammetry point clouds had an average of 95% of their data points located within 1.25 inches of the LiDAR data, while the damaged photogrammetry point clouds had an average of 96%. Both the undamaged and damaged photogrammetry data sets had an average of 97% of their data points located within 1.5 inches. The undamaged photogrammetry point clouds had an average of 97% of their data points located within 1.75 inches of the LiDAR data, while the damaged photogrammetry point clouds had an average of 98%. Both the undamaged and damaged vehicle point clouds had an average of 98% of the points within 2 inches of the LiDAR data. (Table 15, Figure 24).

Table 15. Average number of comparison points for undamaged and damaged vehicle sets at specific distances from the corresponding LiDAR point cloud. Photographs taken with the Canon PowerShot G16 processed through each of the 4 photogrammetry software titles.

Undamaged / Damaged	.25"	.50"	.75"	1.0"	1.25"	1.5"	1.75"	2.0"
Undamaged	57%	80%	89%	93%	95%	97%	97%	98%
Damaged	60%	83%	91%	94%	96%	97%	98%	98%

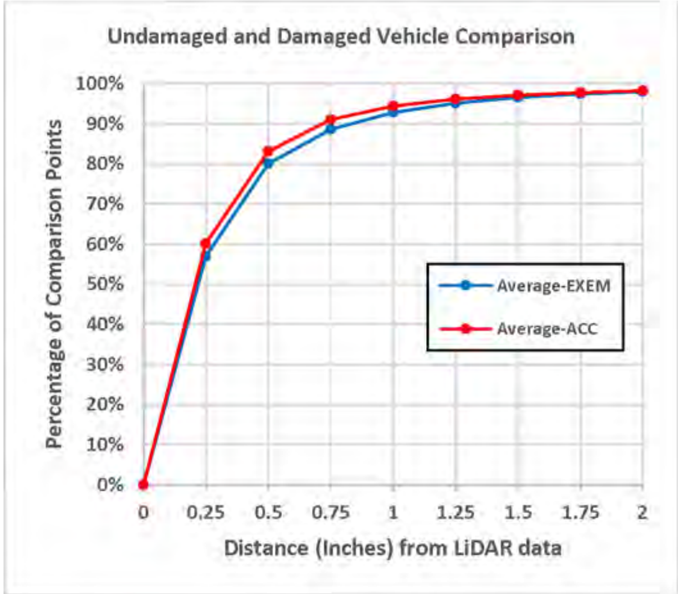

Figure 24. A cumulative probability plot of data from Table 15 with percentage of points over specific distances.

Further Analysis: Photographs and Video Comparison

When comparing the differences in photogrammetry point clouds created from video to those created from photographs, it is clear that photographs create a better point cloud solution. To understand if this had more to do with resolution than a photograph or video format, the total number of pixels used for each was calculated. The average number of pixels used in the ~160 photograph data sets was

1,896,000,000. The average number of pixels used in the video sets was 821,145,600 or nearly half. Because of this difference in total pixels, the photograph data sets where the total number of photos was reduced from 160 to 80, and 40 were considered. The 40 photograph set had a total of 480,000,000 pixels used, or nearly half of the total pixels used in the video solution. The 40 photograph set returned an average of 1,027,802 total comparison points and the video sets returned an average of only 555,374 comparison points. The photograph point clouds were also shown to be more accurate (Figures 25 and 26).

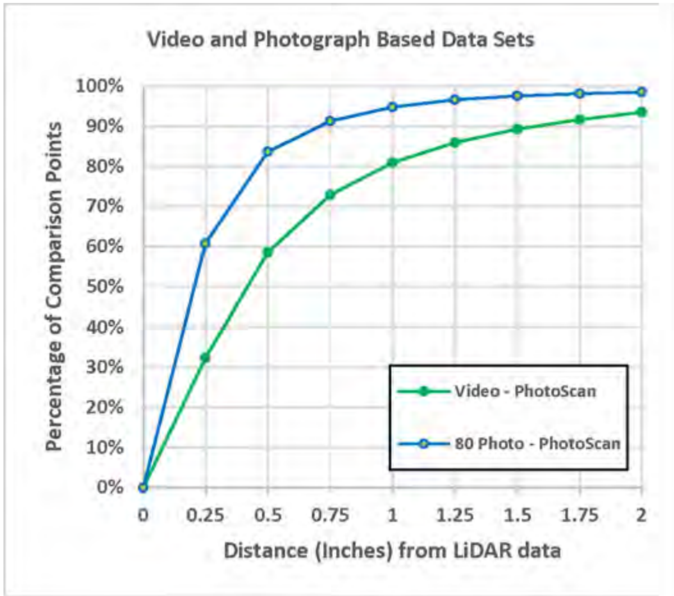

Figure 25. A cumulative probability plot of exemplar vehicle photogrammetry data from Agisoft PhotoScan, Canon PowerShot G16. Both the video and the photograph sets were taken with the Canon PowerShot G16 and processed in Agisoft PhotoScan. The photo set represented was processed with 80 photographs.

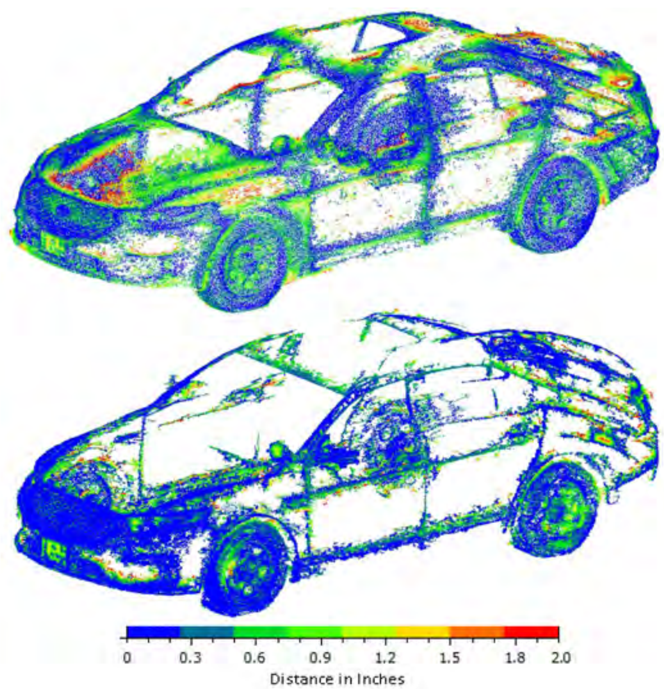

Figure 26. Exemplar vehicle photogrammetry data from Agisoft Photoscan, Canon PowerShot G16. Top: Photogrammetry point cloud from video. Bottom: 40 photo set. Colorization is representative of distance from LiDAR data. (Points beyond 2” are not shown)

Summary/Conclusions

Documenting vehicles for the purpose of generating 3D data through Multi-view 3D reconstruction or photogrammetry software is a relatively quick and inexpensive process that can be accomplished by almost anyone who is comfortable using a tape measure and a camera. Reference markers can be setup in less than five minutes and the entire photograph set of approximately 160 photographs can be taken in less than fifteen minutes. The Canon PowerShot G16, one of the cameras in this study with the best results, can be purchased for less than $400. The camera has several advanced automatic features allowing almost anyone to obtain high quality digital photographs. The entire vehicle documentation, including setup, can be completed in twenty minutes, or less if less photographs are required. This does not include computer processing time within the software. Processing time will be variable and is dependent on software titles, software version, settings within the software, computer specifications or capabilities as well as the number and resolution of photographs.

In our tests comparing the four software titles, Agisoft PhotoScan returned the largest average number of comparison points (1,887,481) and VisualSFM returned the least (645,013). All four titles had an average of nearly 60% of their points within .25” of the LiDAR point cloud data and an average of more than 80% of their points within .5” of the LiDAR data. With additional filtering, it is likely that these percentages can be further improved upon.

All of the cameras used in this study returned hundreds of thousands of 3D data points located within .25” of the LiDAR data. The Canon EOS 5D Mark II and the Canon PowerShot G16 had similar results and both performed better than the GoPro Hero4 Black and the Samsung Galaxy 6 Active cameras. An in depth understanding of what camera factors create this difference in point cloud accuracy is beyond the scope of this paper. Considering how the software analyzes pixels comprising the photographs, it is likely that the number of pixels (resolution) and the quality of pixels (image sensor size, and image compression) are factors.

The photograph point clouds, with a comparable number of total pixels analyzed, returned approximately twice as many data points as the video based point clouds. The photograph point clouds ware also significantly more accurate than the video based point clouds. While it is possible that higher end video cameras may return better results, it seems clear that other factors such as rolling shutter and video compression make photographs a better option than video for this type of photogrammetric processing.

When comparing the damaged and undamaged vehicle data sets, little difference was found in the number of comparison points returned by the photogrammetry software. The damaged vehicle sets did have a ~3% increase in accuracy within .25” of the LiDAR data over the undamaged data. A visual analysis of the damaged areas also revealed that more data points as well as data points with higher accuracy were present in areas where vehicle damage was present.

The data sets where the number of photos in each set was reduced from ~160 photographs to 80, 40, 16, and 8 show a relationship between the number of photographs and the number of comparison points returned from the photogrammetry software. In general the accuracy also decreased with the number of photographs. While effort was given to scale and align each set as accurately as possible, the number of 3D data points on the reference tape markers made point selection more difficult within the data sets with less photographs. This increased difficulty was because of the lack of data points located on the reference markers themselves. It is probable that this dearth of data points accounts for some of the decrease in accuracy for these sets. It is also worth noting that while the sets of 8 photographs were not able to be processed, the tests do not show that the software cannot create a solution using 8 or less photographs. The inability of the software to process our data sets may have to do the photographs that were chosen. For our tests the 8 photograph data sets included photos around the entire vehicle at approximately every 45°. The amount of angular separation between each photo is a foreseeable reason for the software limitations on these sets.

The usefulness of this study and the presented methodology to a damage reconstruction is dependent on how that data is being used. While the results of some of the data sets obtained a large number of data points and were found to be quite accurate, the results are indicative of only the specific study testing and presented methodology. There are a number of variables that should be considered when undertaking a similar photogrammetric project. Surface materials having or causing reflection, refraction, specular highlights surface material, distance from the object(s) of interest, objects that surround the object(s) of interest, lighting, weather conditions and a changing scene, can all have an effect on results.

Multi-view photogrammetry will continue to be developed and will achieve even higher levels of accuracy in the future. This is true from both the hardware side with the development of cameras capable of higher quality photographs with higher resolution, as well as the software side with new photogrammetry software and newer versions of software improving upon what is demonstrated in this paper. Based on the authors' experiences and on the results of this paper, additional cleanup and filtering of data, as well as higher quality and resolution of photographs, will lead to an increased number of photogrammetry data points and greater accuracy.

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Contact Information

2014 Ford Taurus 3D Scan Data from the Faro Focus 3D X 330 used in this study has been made publically available in .pts file format free of charge: www.vehiclescans.com/resources#/resources_articles

The full set of 2014 Ford Taurus photographs taken with a Canon PowerShot G16 are also available to download without charge on the same website.

Upon request, the authors will make available any additional photograph or 3D scan data from this study.

Toby Terpstra
Kineticorp, LLC
(303) 733-1888
tterpstra@kineticorp.com

www.kineticorp.com

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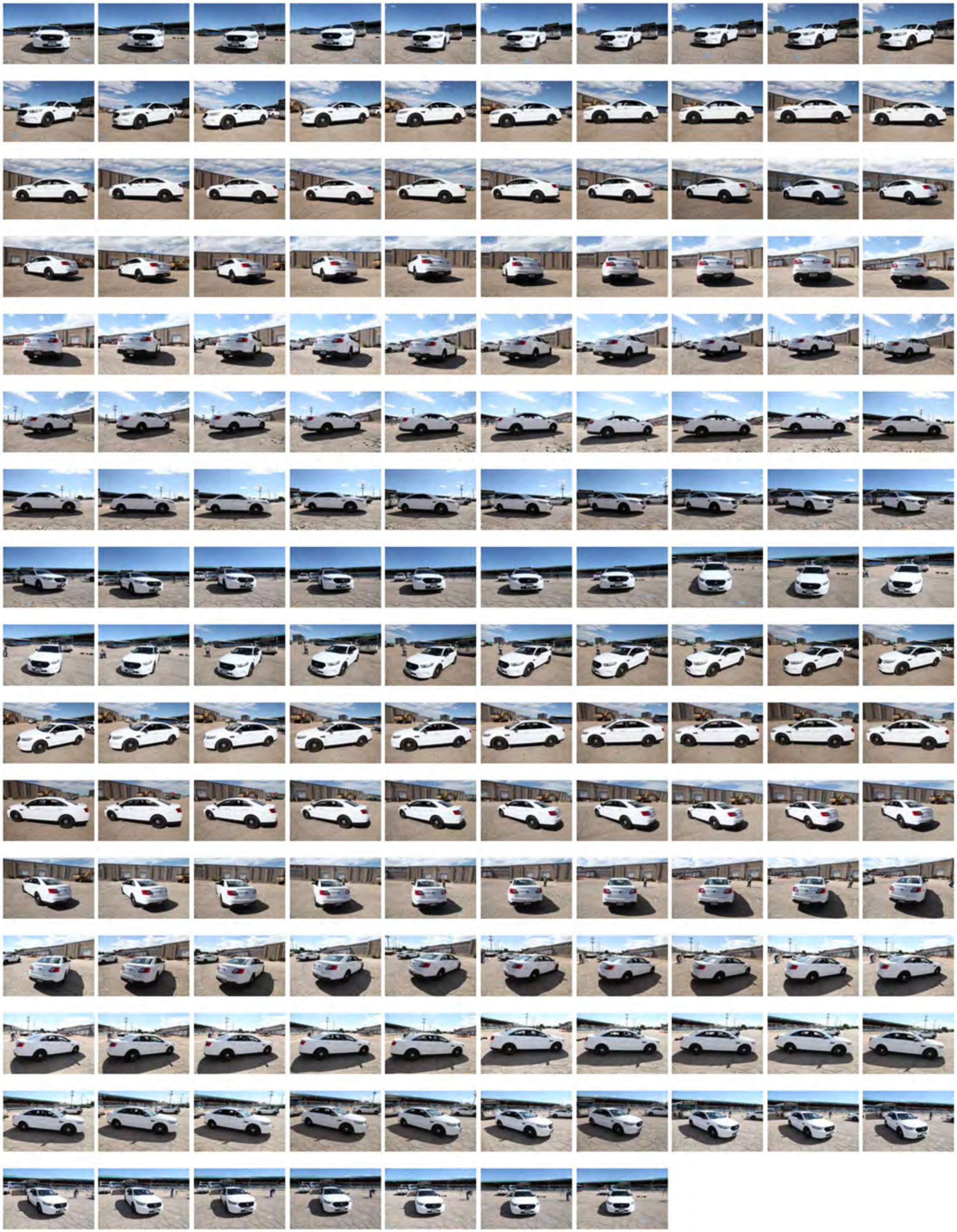
- Wayne Biever for his assistance with statistical analysis.

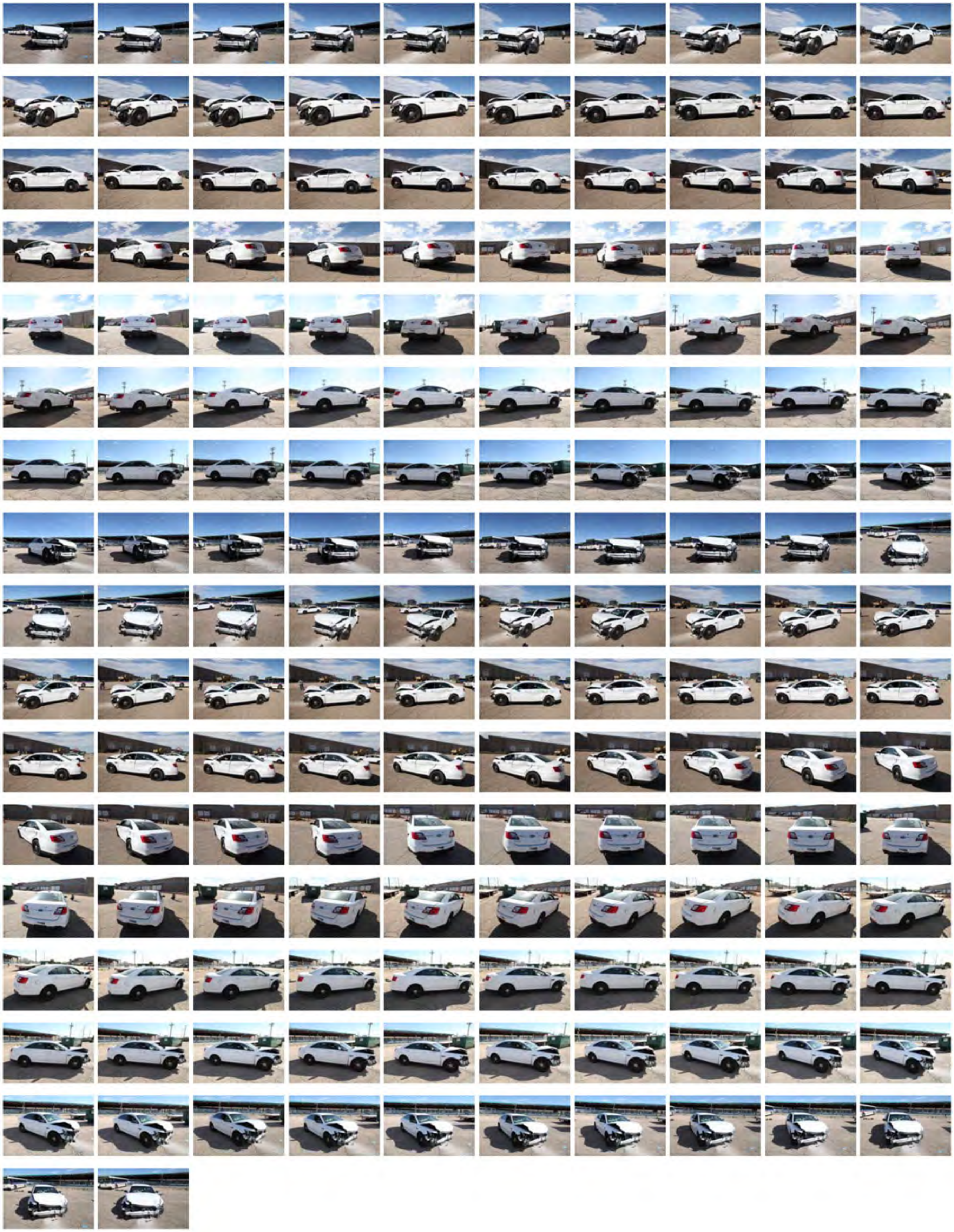
APPENDIX

Appendix A - Complete Photograph Sets by Camera

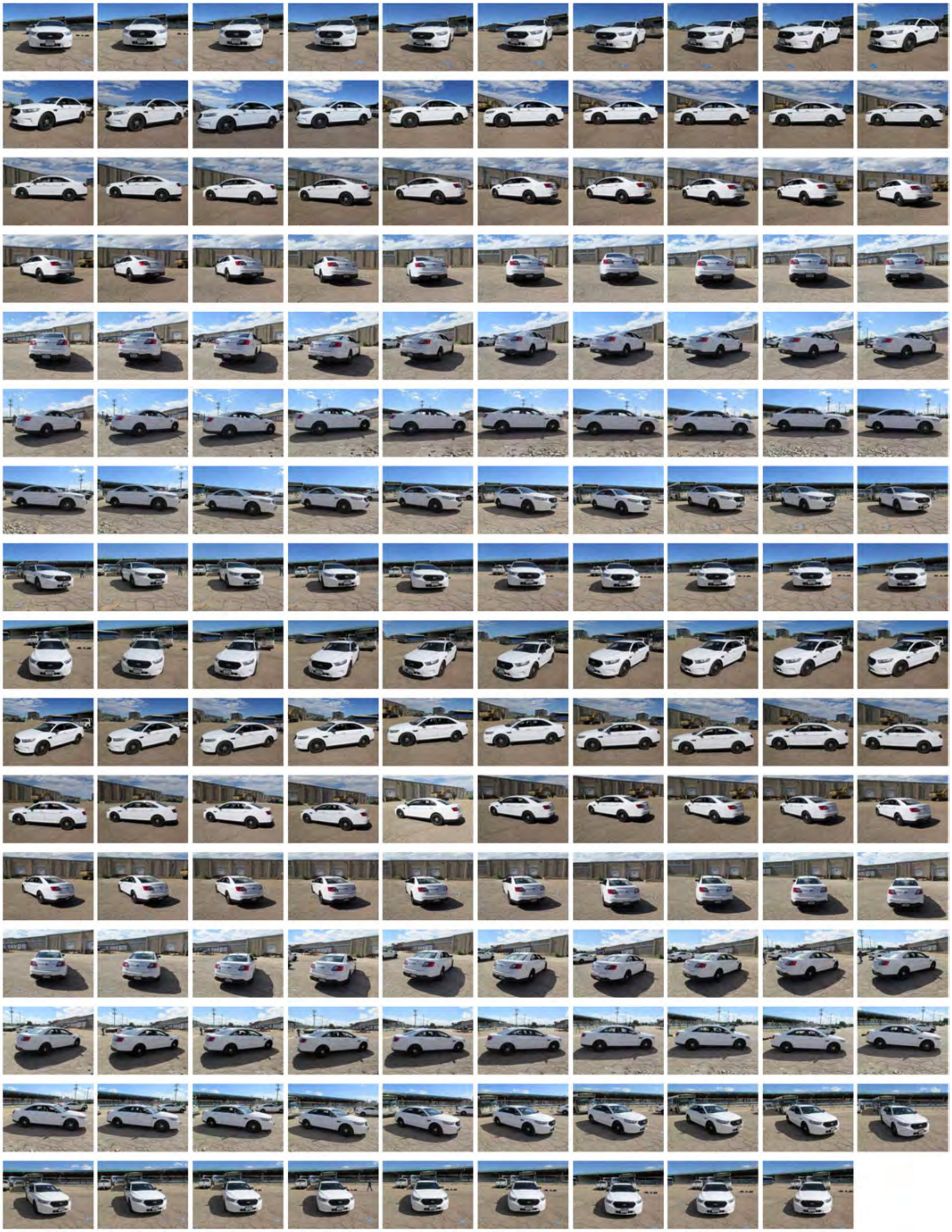
Canon EOS 5D Mark II – Undamaged Vehicle – 157 photographs



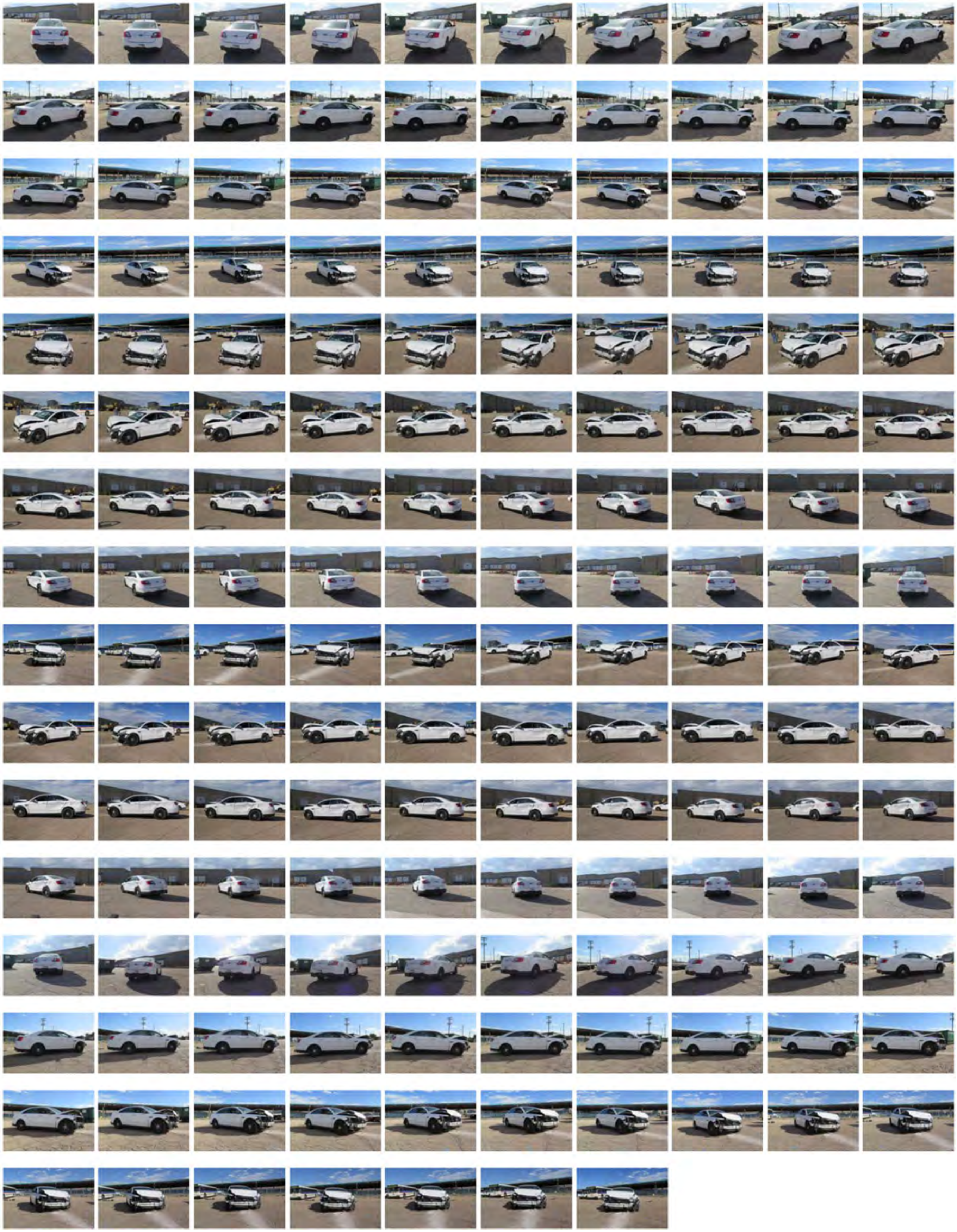
Canon EOS 5D Mark II – Damaged Vehicle – 162 photographs



Canon PowerShot G16 – Undamaged Vehicle – 159 photographs

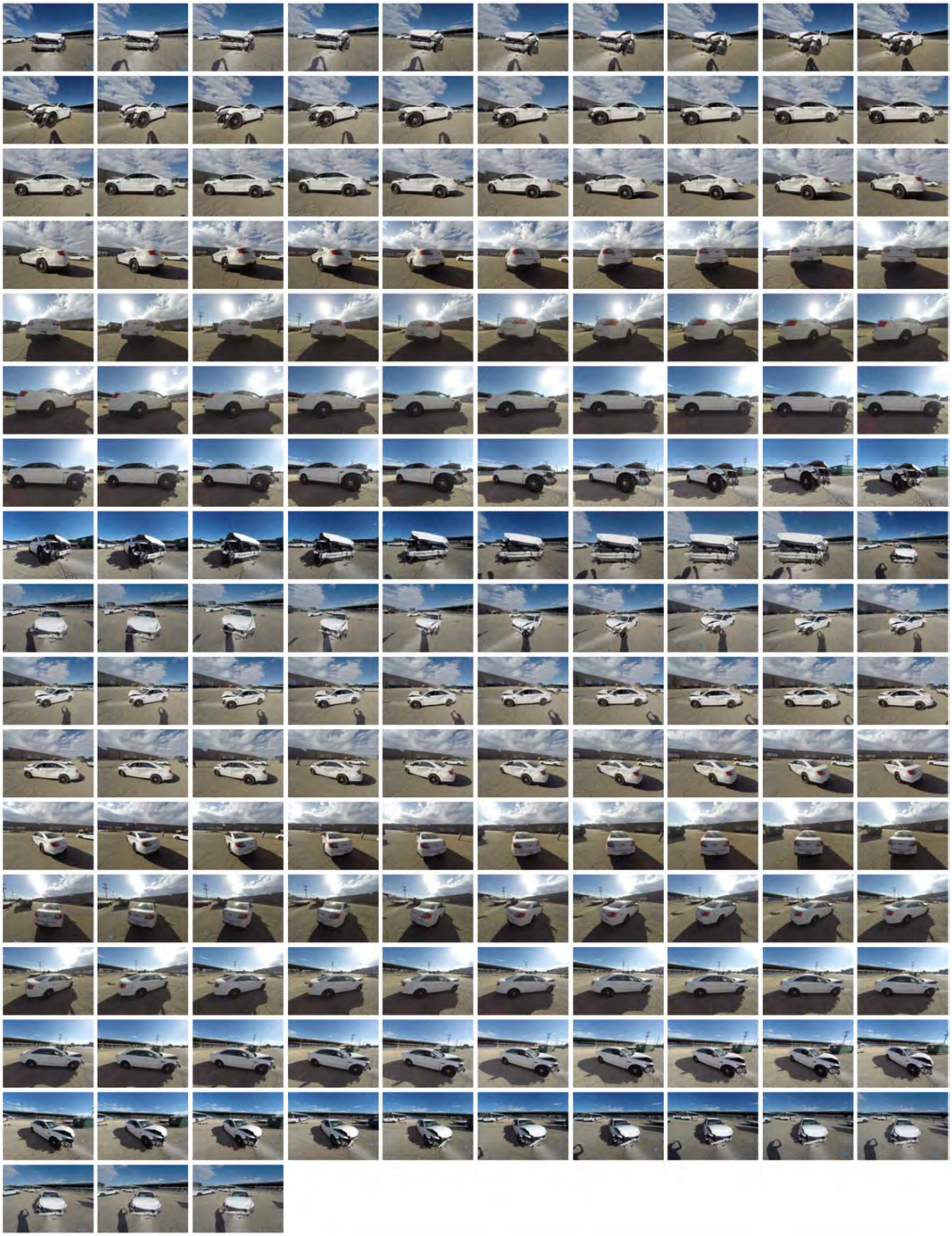


Canon PowerShot G16 – Damaged Vehicle – 157 photographs



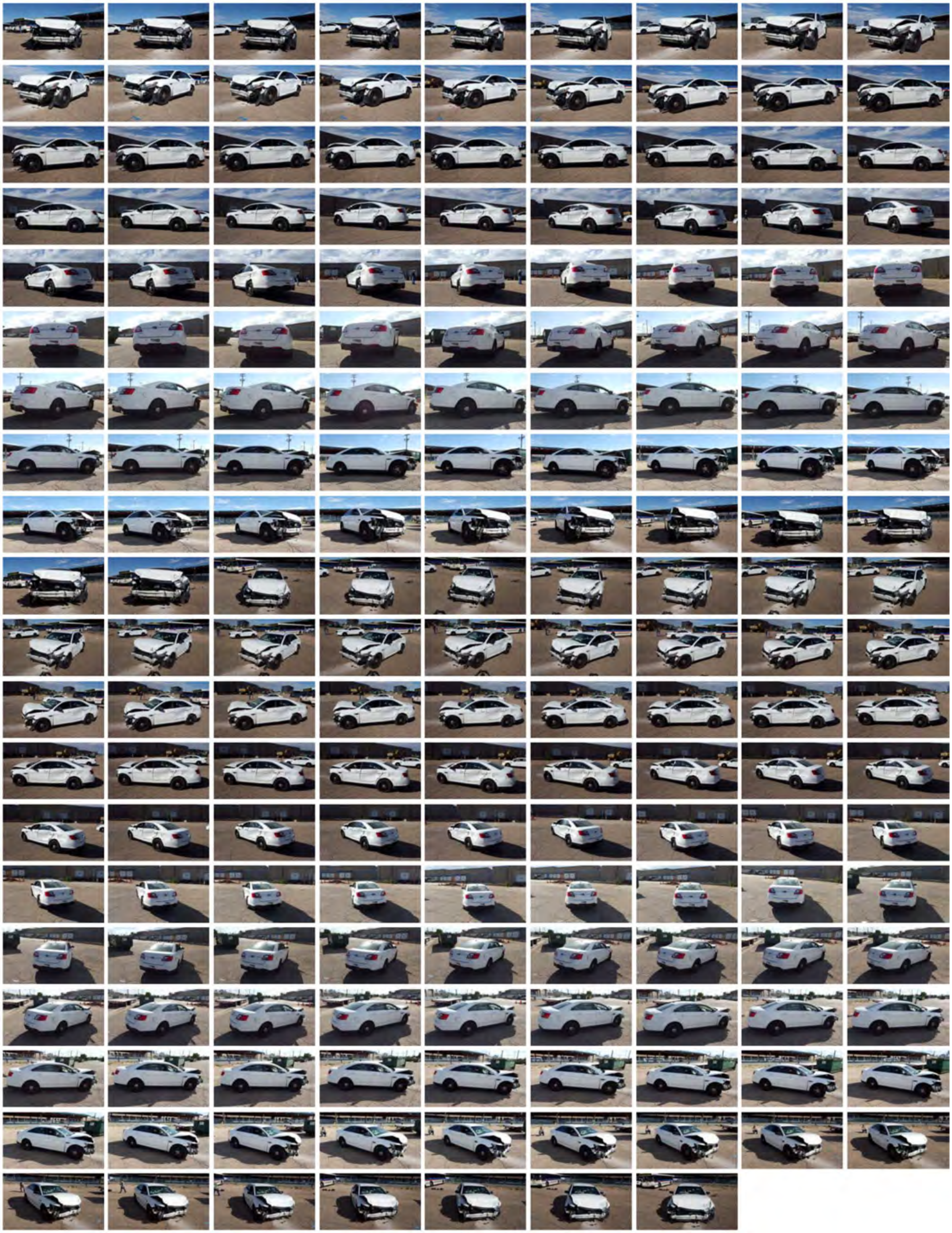
GoPro Hero4 Black – Undamaged Vehicle – 161 photographs

GoPro Hero4 Black – Damaged Vehicle – 163 photographs



Samsung Galaxy S6 Active – Undamaged Vehicle – 162 photographs

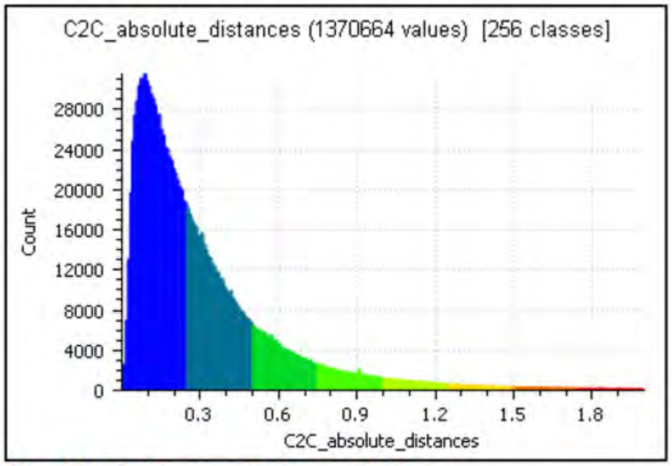
Samsung Galaxy S6 Active – Damaged Vehicle – 178 photographs



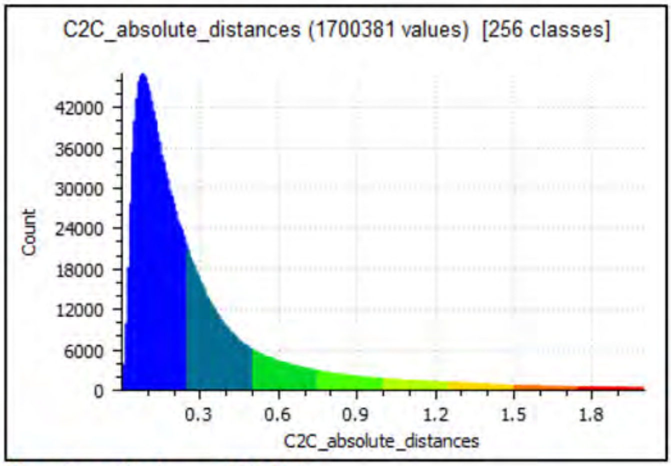
Appendix B - Histograms of Photogrammetry Software Data Distance from LiDAR Data

Canon PowerShot G16 - Full Photo Sets - Damaged and Undamaged Vehicles

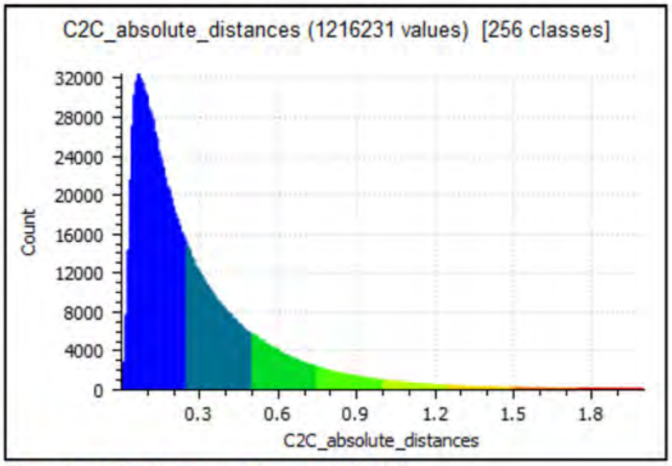
Histogram colorization based on quarter inch increments



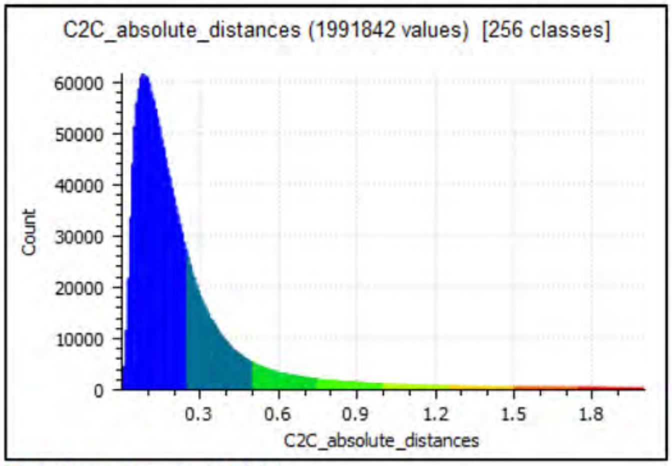
PhotoModeler Scanner, Undamaged Vehicle
1,370,664 total comparison points
13,719 points beyond 2 inches (~1%)
Maximum: 14.6 inches



PhotoScan, Undamaged Vehicle
1,700,381 total comparison points
42,558 points beyond 2 inches (~2.5%)
Maximum: 13.3 inches

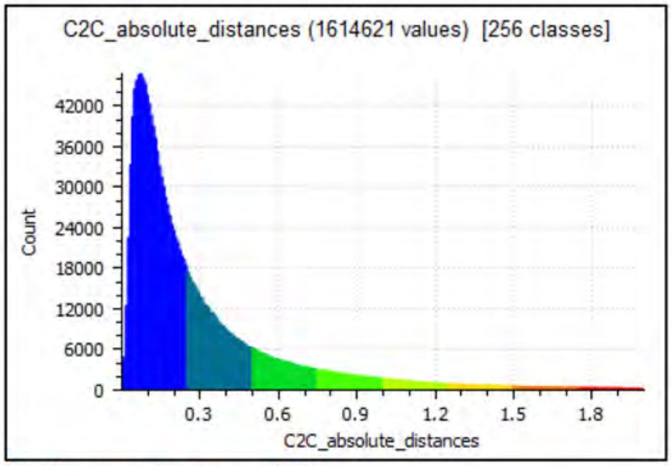


PhotoModeler Scanner, Damaged Vehicle
1,216,231 total comparison points
11,564 points beyond 2 inches (~1%)
Maximum: 10.2 inches

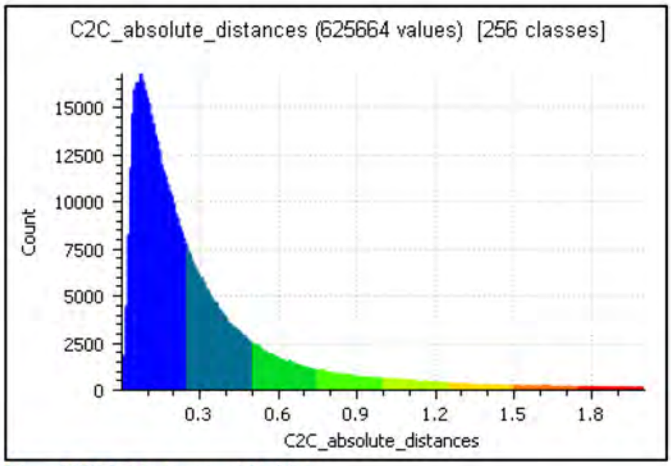


PhotoScan, Damaged Vehicle
1,991,842 total comparison points
40,180 points beyond 2 inches (~2%)
Maximum: 10.7 inches

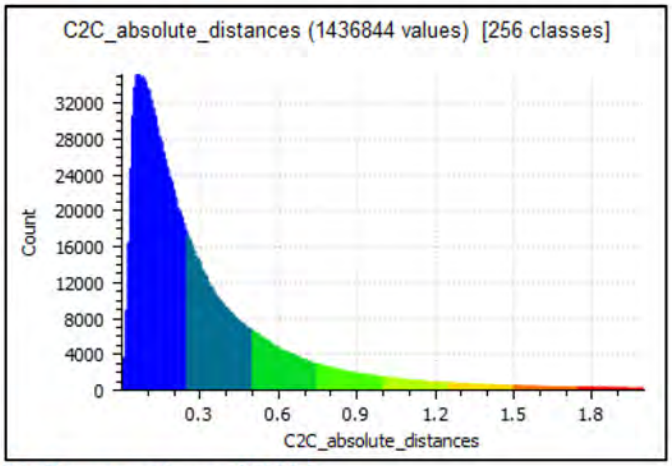
Canon PowerShot G16 - Full Photo Sets - Damaged and Undamaged Vehicles Histogram colorization based on quarter inch increments



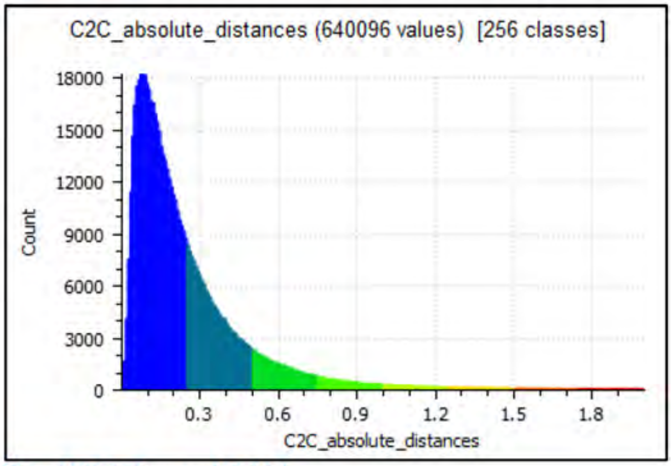
Pix4Dmapper, Undamaged Vehicle
1,614,621 total comparison points
33,388 points beyond 2 inches (~2%)
Maximum: 16.9 inches



VisualSFM, Undamaged Vehicle
625,664 total comparison points
15,397 points beyond 2 inches (~2.5%)
Maximum: 7.7 inches



Pix4Dmapper, Damaged Vehicle
1,436,844 total comparison points
39,973 points beyond 2 inches (~2.8%)
Maximum: 21 inches

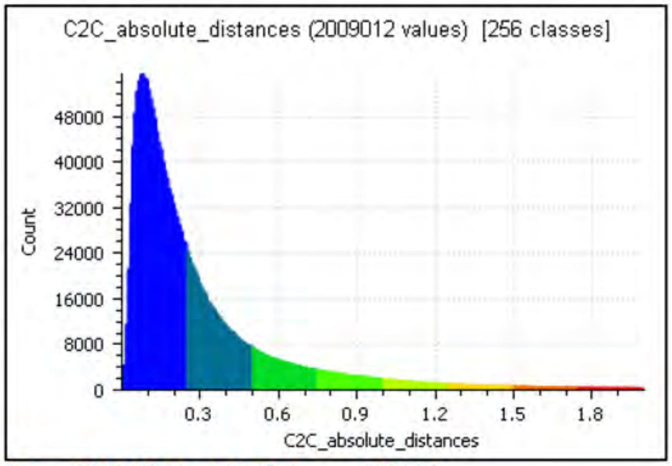


VisualSFM, Damaged Vehicle
640,096 total comparison points
8,867 points beyond 2 inches (~1.4%)
Maximum: 7 inches

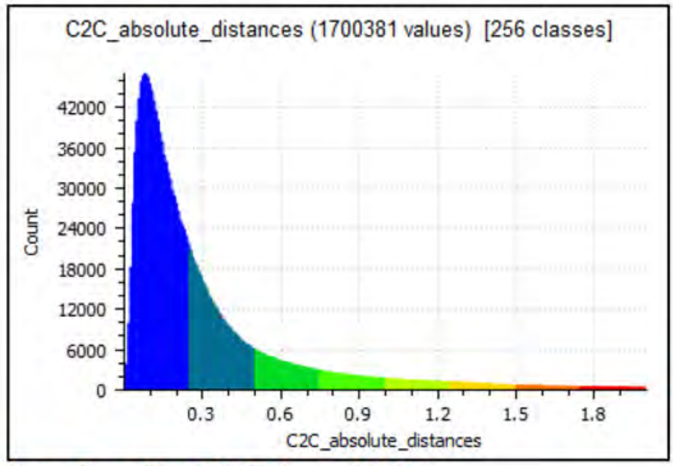
Appendix C - Histograms of Camera Specific Photogrammetry Software Data Distance from LiDAR Data

Agisoft PhotoScan v. 1.1.6 - Full Photo Sets - Damaged and Undamaged Vehicles

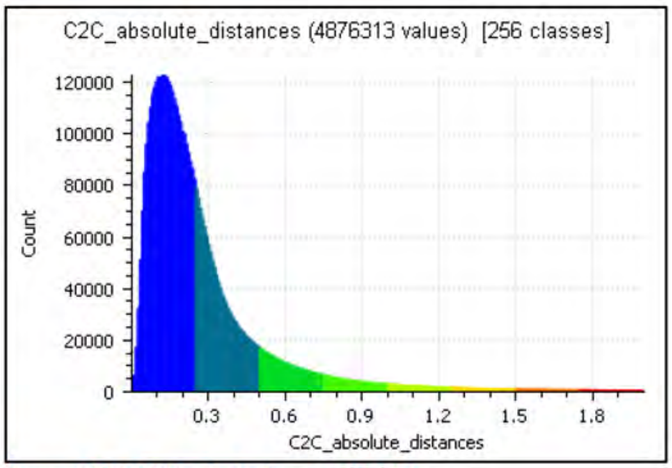
Histogram colorization based on quarter inch increments



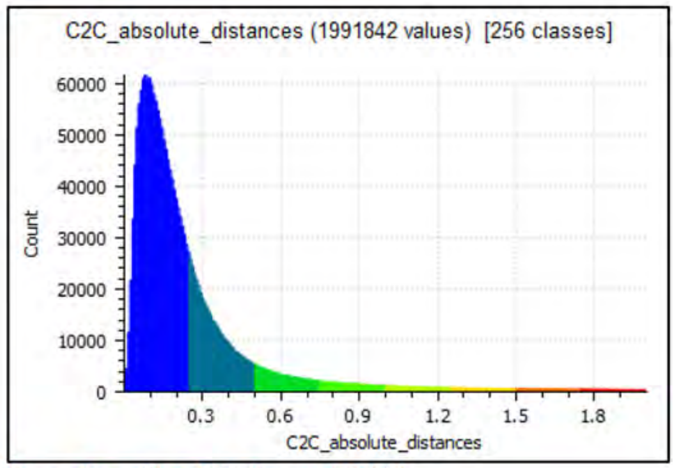
Canon EOS 5D Mark II, Undamaged Vehicle
2,009,012 total comparison points
43,194 points beyond 2 inches (~2.2%)
Maximum: 7.7 inches



Canon PowerShot G16, Undamaged Vehicle
1,700,381 total comparison points
42,558 points beyond 2 inches (~2.5%)
Maximum: 13.3 inches

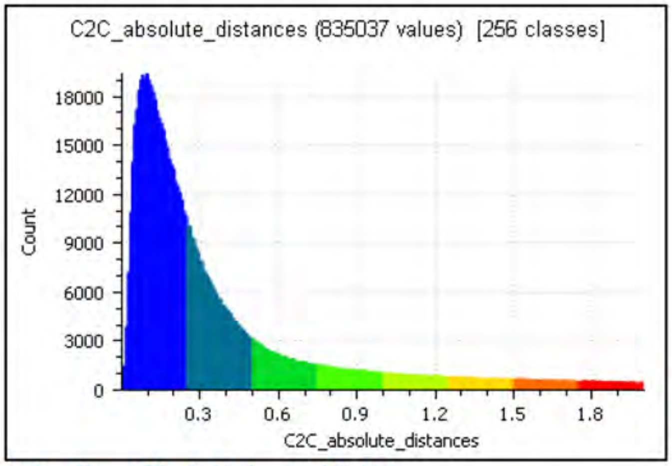


Canon EOS 5D Mark II, Damaged Vehicle
4,876,313 total comparison points
74,607 points beyond 2 inches (~1.5%)
Maximum: 12 inches

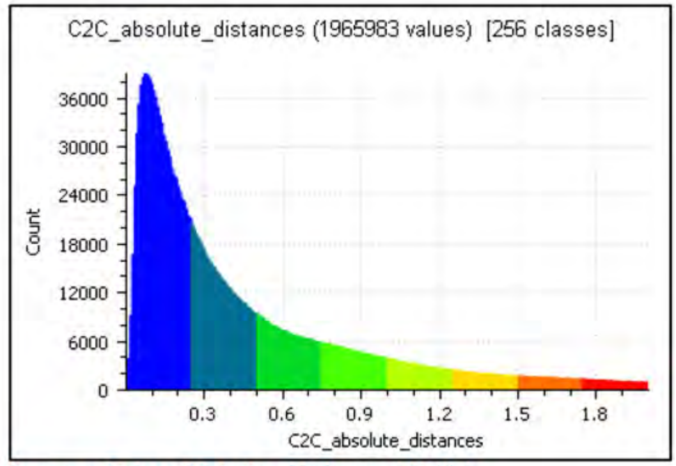


Canon PowerShot G16, Damaged Vehicle
1,991,842 total comparison points
40,180 points beyond 2 inches (~2%)
Maximum: 10.7 inches

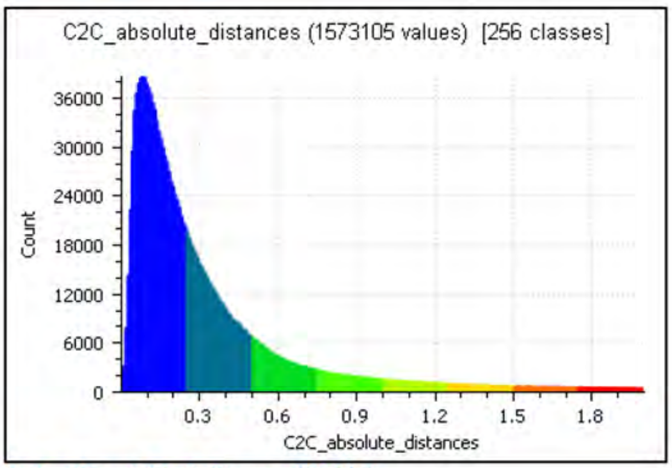
Agisoft PhotoScan v. 1.1.6 - Full Photo Sets - Damaged and Undamaged Vehicles Histogram colorization based on quarter inch increments



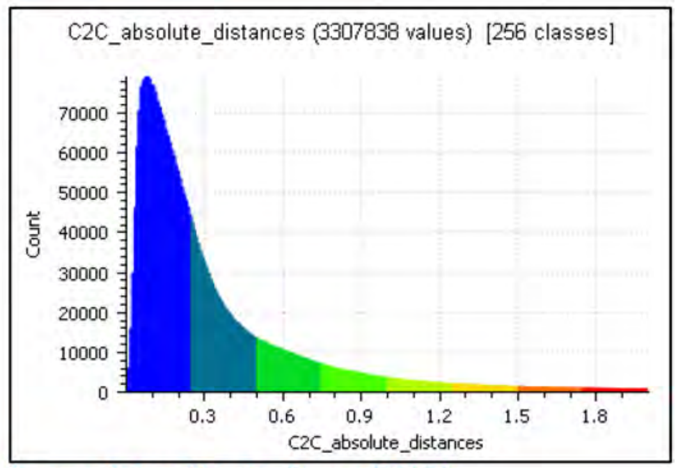
GoPro Hero4 Black, Undamaged Vehicle
835,037 total comparison points
105,019 points beyond 2 inches (~12.6%)
Maximum: 22.1 inches



Samsung Galaxy S6 Active, Undamaged Vehicle
1,965,983 total comparison points
162,554 points beyond 2 inches (~8.3%)
Maximum: 15.8 inches



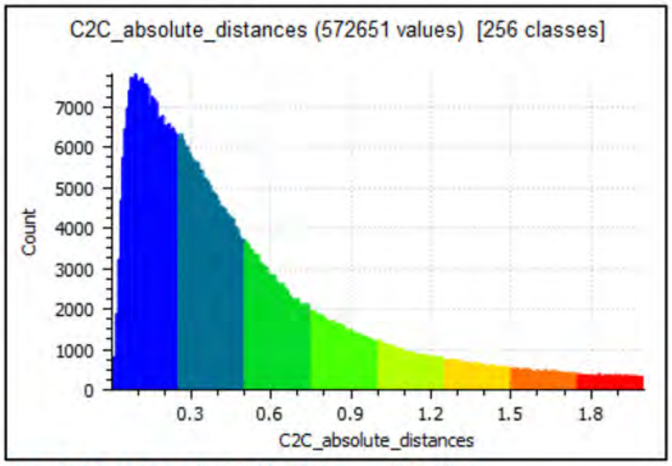
GoPro Hero4 Black, Damaged Vehicle
1,573,105 total comparison points
68,034 points beyond 2 inches (~4.3%)
Maximum: 17.6 inches



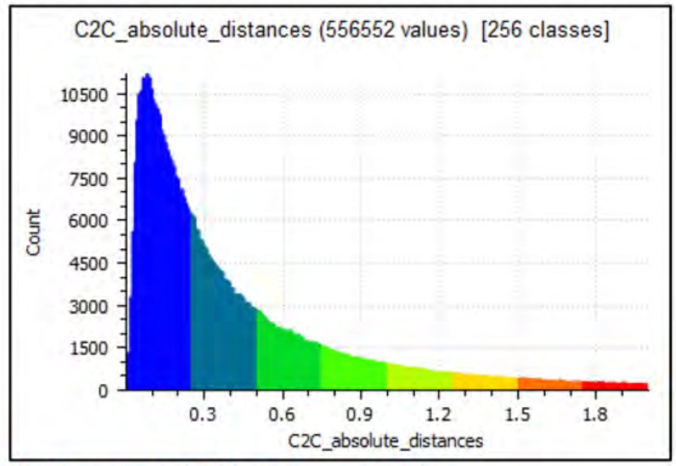
Samsung Galaxy S6 Active, Damaged Vehicle
3,307,838 total comparison points
96,068 points beyond 2 inches (~2.9%)
Maximum: 10.9 inches

Appendix D - Histograms of Video Based Photogrammetry Software Data Distance from LiDAR Data

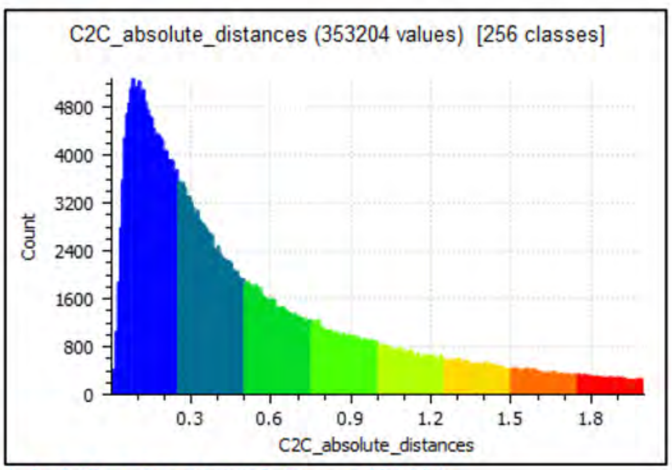
Canon PowerShot G16 - Video Sets - Damaged and Undamaged Vehicles
Histogram colorization based on quarter inch increments



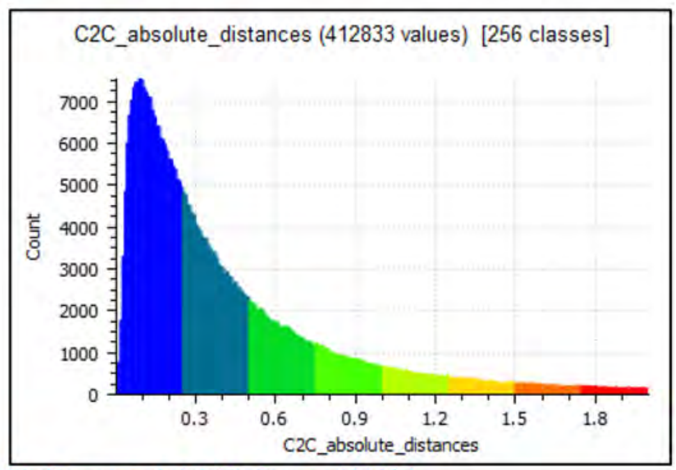
Agisoft PhotoScan (v.1.1.6), Undamaged Vehicle
572,651 total comparison points
39,667 points beyond 2 inches (~6.9%)
Maximum: 16.6 inches



Pix4Dmapper (v.2.0.83), Undamaged Vehicle
556,552 total comparison points
31,703 points beyond 2 inches (~5.5%)
Maximum: 19.7 inches

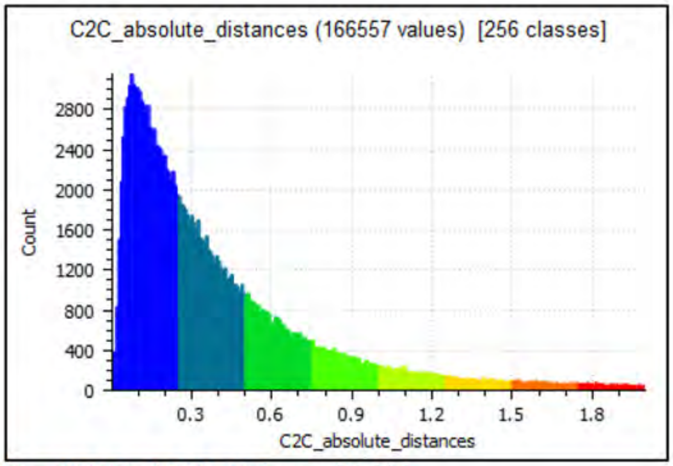


Agisoft PhotoScan (v.1.1.6), Damaged Vehicle
353,204 total comparison points
39,119 points beyond 2 inches (~11%)
Maximum: 24.7 inches

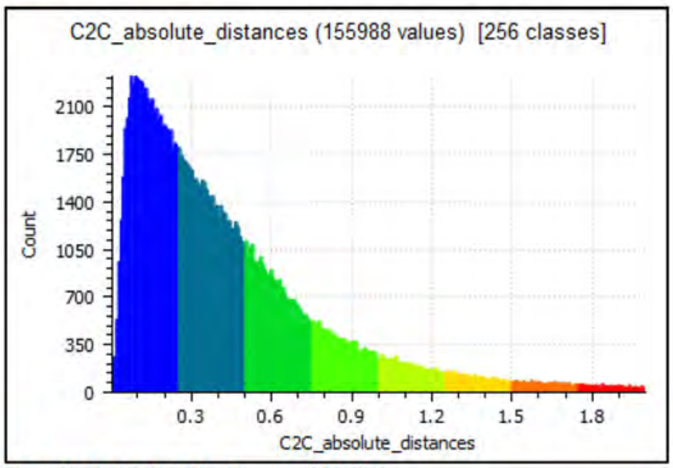


Pix4Dmapper (v.2.0.83), Damaged Vehicle
412,833 total comparison points
18,029 points beyond 2 inches (~4.4%)
Maximum: 22.3 inches

Canon PowerShot G16 - Video Sets - Damaged and Undamaged Vehicles Histogram colorization based on quarter inch increments



VisualSFM (v.0.5.26), Undamaged Vehicle
166,557 total comparison points
10,480 points beyond 2 inches (~.6.2%)
Maximum: 19.6 inches

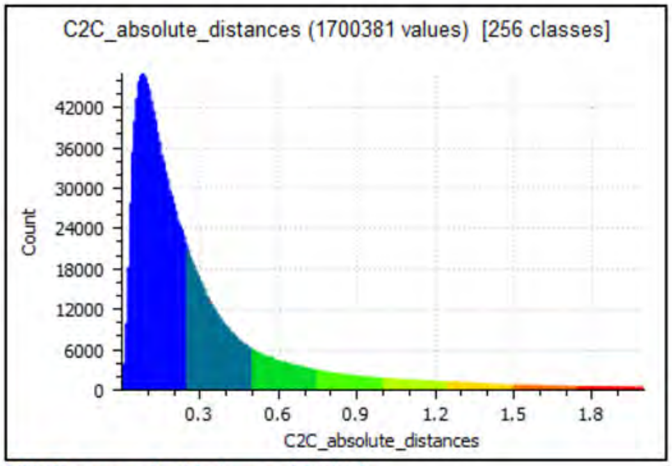


VisualSFM (v.0.5.26), Damaged Vehicle
155,988 total comparison points
7,025 points beyond 2 inches (~4.5%)
Maximum: 18.9 inches

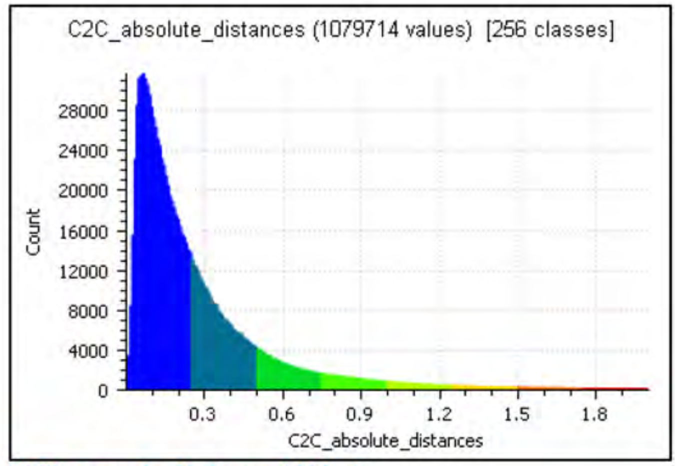
Appendix E - Histograms of Specific Photograph Amounts - Photogrammetry Software Data Distance from LiDAR Data

Canon PowerShot G16 -Agisoft PhotoScan (v.1.1.6) - Damaged and Undamaged Vehicles

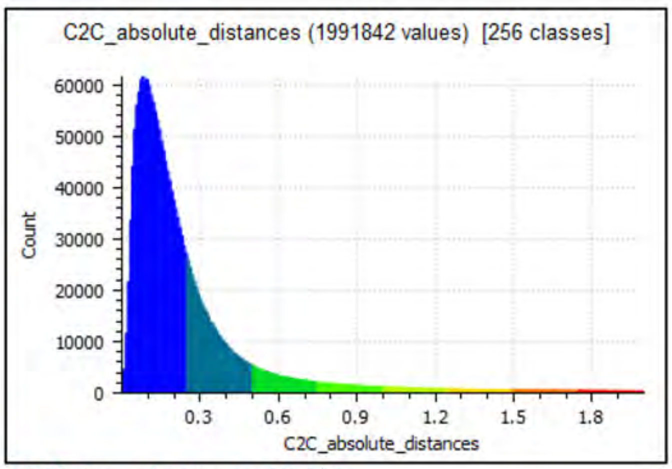
Histogram colorization based on quarter inch increments



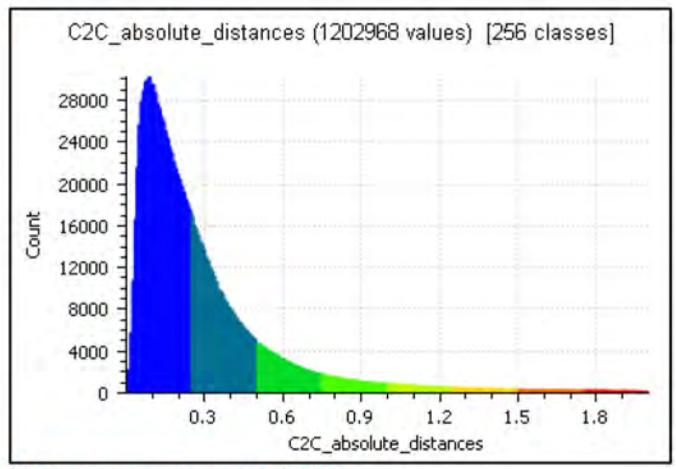
159 Photographs, Undamaged Vehicle
1,700,381 total comparison points
42,558 points beyond 2 inches (~2.5%)
Maximum: 13.3 inches



80 Photographs, Undamaged Vehicle
1,079,714 total comparison points
15,030 points beyond 2 inches (~1.4%)
Maximum: 7.9 inches

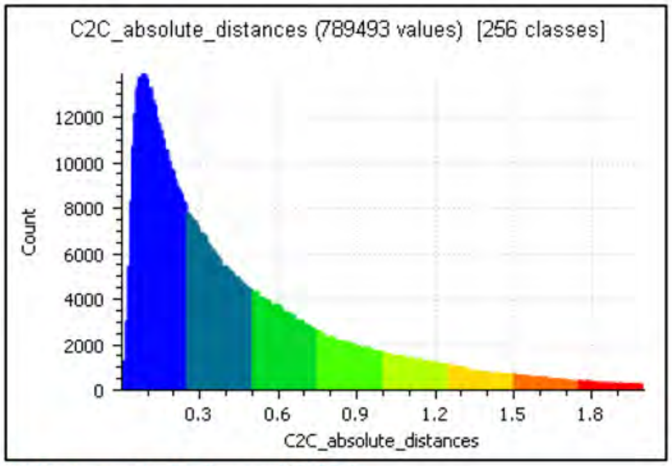


157 Photographs, Damaged Vehicle
1,991,842 total comparison points
40,180 points beyond 2 inches (~2%)
Maximum: 10.7 inches

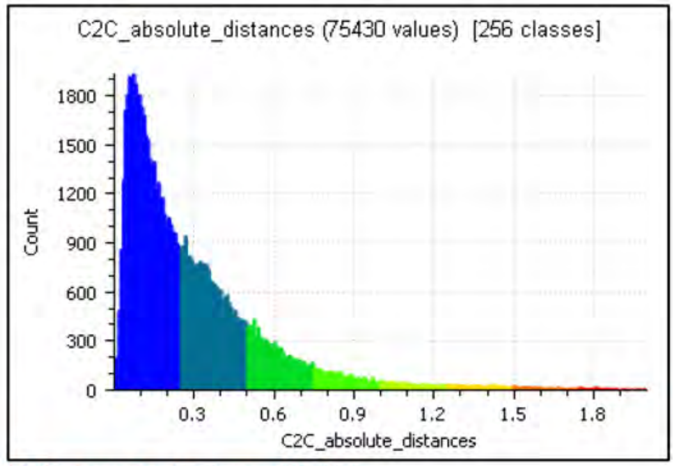


80 Photographs, Damaged Vehicle
1,202,968 total comparison points
23,669 points beyond 2 inches (~2%)
Maximum: 29.9 inches

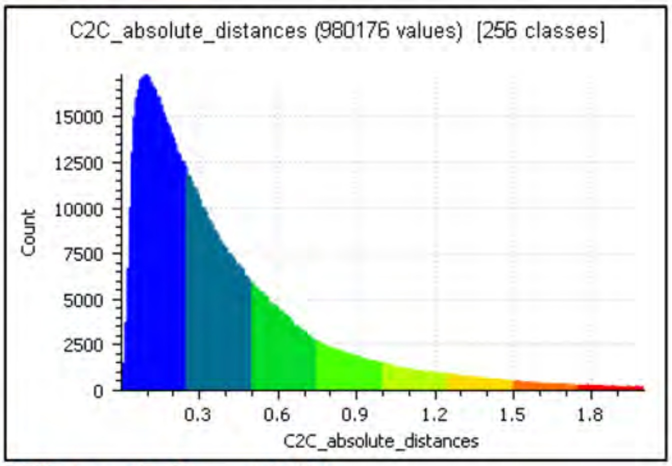
Canon PowerShot G16 -Agisoft PhotoScan (v.1.1.6) - Damaged and Undamaged Vehicles Histogram colorization based on quarter inch increments



40 Photographs, Undamaged Vehicle
789,493 total comparison points
27,938 points beyond 2 inches (~3.5%)
Maximum: 9.8 inches



16 Photographs, Undamaged Vehicle
75,430 total comparison points
747 points beyond 2 inches (~1%)
Maximum: 6.6 inches



40 Photographs, Damaged Vehicle
980,176 total comparison points
24,758 points beyond 2 inches (~2.5%)
Maximum: 17.8 inches

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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