

ACCURACY COMPARISONS OF IPHONE 12 PRO LIDAR OUTPUTS

by

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A thesis submitted to the  
Faculty of the Graduate School of the  
University of Colorado in partial fulfillment  
of the requirements for the degree of  
Master of Science  
Media Forensics Program

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Date: December 18, 2021

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Accuracy Comparisons of iPhone 12 Pro LiDAR Outputs

Thesis directed by Associate Professor Catalin Grigoras

### **ABSTRACT**

The Apple iPhone 12 Pro is a powerful handheld computer that is capable of documenting crime scene data with two distinct methods. Method one utilizes the iPhones LiDAR sensor, method two utilizes the iPhones photographic capability. Both methods can be used to analyze real-world objects or environments to collect data on their shape and color. The collected data can then be used to construct digital three-dimensional point clouds for analysis. Four applications of these methodologies were tested and compared against the accuracy of a Faro Focus 3D scanners 3D point cloud. Two applications will test the iPhone 12 Pro's LiDAR scanning accuracy and two applications will test the photogrammetric processing accuracy of digital images captured using the iPhone camera. The LiDAR applications tested were EveryPoint version 2.9 and Polycam version 2.0.1, both apps are available for download from Apple's App Store. The photogrammetric processing software's tested were Autodesk's Recap Photo version 22.1 and Pix4Dmapper version 4.6.4, both software's are used to process the iPhones digital images in a desktop setting. Three testing methodologies were used to evaluate the results, method one was cloud to cloud comparison measuring point to point distance, method two is a distance measurement comparison between various objects in the simulated crime scene, and method three observes the clarity and positional accuracy of a chalk outline.

The form and content of this abstract are approved. I recommend its publication.

Approved: Catalin Grigoras

## **DEDICATION**

I dedicate this work to my wife Clara, whose love and support continuously lifts my efforts. Her hard work and effort in all of life's tasks is truly inspirational, and I would like to dedicate this research and this entire Master's Degree to her.



## **ACKNOWLEDGEMENTS**

I would like to thank the many professors involved in the Media Forensics Department at the University of Colorado Denver. This work would not have been possible without their guidance and patience.

I would also like to thank my colleagues working at Kineticorp, their advice in all things forensics was more valuable to me than thoughts can express.

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## **LIST OF ABBREVIATIONS**

3D – Three Dimensional

CPU – Central Processing Unit

GPU – Graphics Processing Unit

LiDAR – Light Detection and Ranging

SoC – System on Chip

ToF – Time of Flight

# CHAPTER I

## INTRODUCTION

The concept of a computer that has the ability to make a phone call, search the internet, fly a drone, take a high-resolution low light photograph, record a video at 60 frames per second in 4K, and perform a dense LiDAR scan is a reality that seemed fiction just a few years ago. The iPhone 12 Pro's introduction to the consumer market by Apple in late 2020 represents a truly amazing amalgamation of all of these varied digital technologies and houses them into one powerful pocket-sized computer.

Laser scanning surveys can be of considerable use in jury trials, for example, in a case where the location supports the use of a high-definition survey, scanning enables the production of video realistic simulated environments [01]. Currently, the collection of 3-dimensional point cloud data would be reserved for only the most crucial investigations of homicides or traffic accidents that result in fatalities because budgets for equipment and training are high. What about the lesser crimes or accidents, would more thorough collections of this valuable 3D data become common if the investigators had access to devices and techniques that would make this task less costly, more efficient, and just as accurate?

With the invention of the iPhone 12 Pro's new LiDAR or Light Detection and Ranging sensor, and the increased capability of the iPhone's camera array system, the iPhone has two powerful and budget friendly forensic tools ready for use. However, it is unwise to assume that this powerful new device can deliver the accurate results that forensic investigators should expect without the knowledge on how to acquire and process this data. This paper will look at the acquisition techniques that are needed to collect and process effective 3D data, and will measure the accuracies of the data collected using the phone's data samples against the 3D data collected with the widely used Faro Focus 3D laser scanner.



## CHAPTER II

### TECHNICAL OVERVIEW

#### The iPhone 12 Pro

The heart of this phone is its A14 bionic chip. The A14 is considered a system-on-chip or SoC device. Like a typical electronics system, an SoC consists of processing elements, I/O devices, storage elements and an interconnection structure linking them all together [02]. The A14 combines what is considered separate components in a modern desktop computer onto a single microchip. These components consist of a six core CPU, a GPU, a Neural Engine, ram, audio, and image processing all stacked together on the industry's first 5nm chip set (the previous chip set being 7nm architecture). That means smaller chip features and more transistors in a given amount of area [03]. Moore's law is demonstrated here by comparing the A14 Bionics benchmark score to a top-of-the-line desktop processor available approximately 10 years ago, the Intel Core i7-990X Processor Extreme Edition (a 32nm chip set architecture) [04]. PassMark Software gives the A14 a CPU benchmark of 8,534, and the Intel i7 a score of 7,262 [05]. This is a test of the CPU and its ability to perform a set of processing tests and gives insight to the relative speed of the processor, which is only one component of many on the SoC designed chip.

The iPhone's 12 Pro comes equipped with a LiDAR scanner, however this is not the only mobile phone device with laser scanning capabilities. The Time-of-Flight sensors on some Android phones and the LiDAR sensor on the iPhone are comparable. Both use lasers as an illumination source and the same Time-of-Flight technique to measure distance and map the surroundings. Android phones employ a scanner-less LiDAR device, while the iPhone 12 Pro uses a scanner-type LiDAR [06]. The distinctions of these two types of LiDAR are not tested in this paper but advantages and disadvantages are had by both types of scanning devices.

The iPhones 12 Pro's cameras are managed by Apple's Deep Fusion system which is a series of processing steps performed as each photo is taken. Apple's camera sensor captures multiple images and processes them through the A14's image signal processor, the CPU computes the alignment of the frames,

the GPU pre-processes the images before running them through the Neural Engine (machine learning), and finally post-processing is done back within the GPU [07]. This combined set of steps is known as Deep Fusion which is essentially designed to help eliminate noise in the photo. The iPhone 12 Pro features four individual cameras, one front facing and three back facing. For testing purposes this paper will use the default “Wide” 12 mega pixel back facing camera (Figure 01). This camera features a 7-element lens, with a 26mm focal length, and optical image stabilization [08].



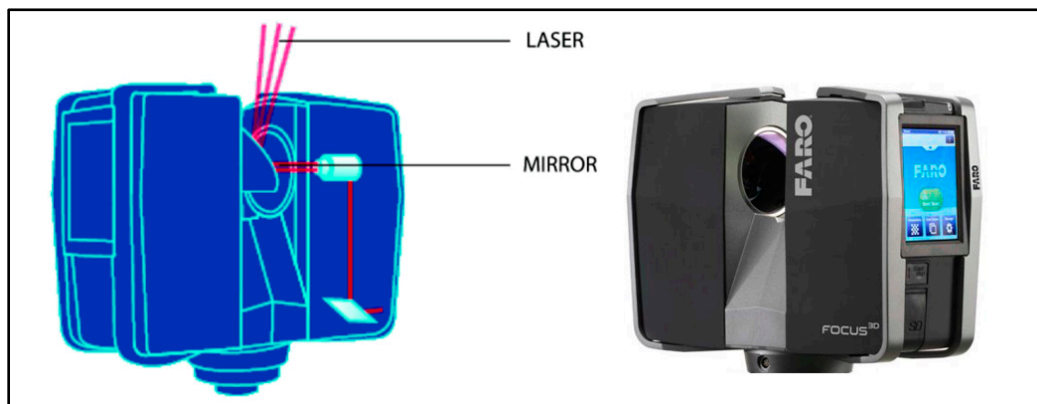
*Figure 01. The iPhone 12 Pro Max Front and Back*

The computing and graphical power of modern mobile devices, such as the iPhone 12 Pro, is sufficient for the integration of sensors which can record the environment and the position of the device itself, and a point cloud can be acquired in real time with immediate visualization of results. This point cloud can then be continuously extended and corrected, and an integrated RGB camera enables the point cloud to be colored [02].

## The Faro Focus 3D

The Faro Focus 3D scanner will provide the benchmark point cloud data set for this paper. This widely used tool works by sending an infrared laser beam into the center of its rotating mirror (Figure 02). The mirror deflects the laser beam on a vertical rotation around the environment being scanned, and scattered light from the surrounding objects is then reflected back into the scanner [09].

To measure the distance, the Focus 3D machine uses phase shift technology, where the constant waves of infrared light of varying lengths are projected outward from the scanner. Upon contact with an object, they are reflected back to the scanner [09]. The distance from the scanner to the object is accurately determined by measuring the phase shifts in the waves of the infrared light. The accuracy of this machine is apparent with a ranging error of  $\pm 2\text{mm}$  at 10m [10]. The scanner was used to record six separate scans placed equidistantly in an area measuring approximately 5.6m in length, 3m in width, and 3m in height, an ideal range to maximize the accuracy of the scanner.



*Figure 02. The Faro Focus 3D Laser Scanner*

### 3D Laser Scanners Explained

The term laser scanning is used to describe the controlled steering of laser beams followed by a distance measurement at every pointing direction [09]. This method, often called 3D object scanning or 3D laser scanning, is used to rapidly capture shapes of objects, buildings, and landscapes. The purpose of a laser scanner is usually to create a point cloud of geometric samples on the surface of a subject. These

points can then be used to extrapolate the shape of the subject, a process called reconstruction. If color information is collected at each point, then the colors on the surface of the subject can also be determined.

3D laser scanning was first created in the 1960's, used lights, cameras, and projectors to perform this task. After 1985 these slower systems were replaced with scanners that could use white light lasers and shadowing to capture a given surface. Fast forward to today's most widely used 3D scanners and you can subcategorize them into two distinct groups, Time-of-Flight (ToF) and Phase-Shift [09].

The ToF rangefinder emits a short laser pulse towards the target and reflected on its surface. A part of the energy then returns to the scanner detector where the sending and arrival time is measured [08]. An example of a ToF 3D scanner is the widely used Leica ScanStation C-10, as well as the iPhone 12 Pro's LiDAR sensor. Since the speed of light is known, the accuracy of a ToF 3D laser scanner depends on how precisely the instrument can measure the time 3.3 picoseconds, the approximate time taken for light to travel 1 millimeter [11]. LiDAR, which stands for Light Detection and Ranging, is often used in military context to describe a method of data collection which uses pulsed light and a Time-of-Flight measurement system to record object information.

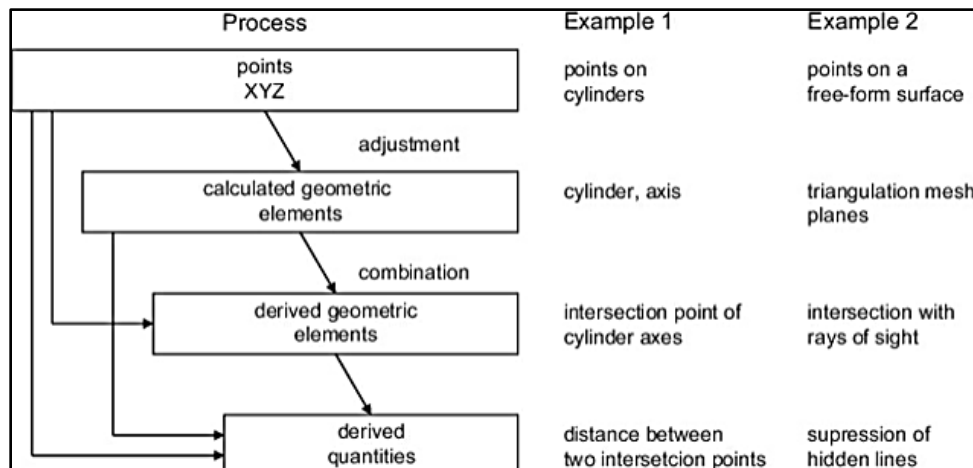
The Phase-Shift rangefinder method uses distance to determine the phase difference between the sent and received waveforms. An example of a widely used Phase-Shift 3D scanner would be the Faro Focus 3D, which is the instrument this paper used to gather the benchmark or base truth point cloud data set the iPhone examples will be compared to. Phase-Shift laser scanners work by comparing the phase shift in the reflected laser light to a standard phase, which is also captured for comparison. This method is similar to Time-of-Flight detection except that the phase of the reflected laser light further refines the distance detection.

## Photogrammetry Explained

Photogrammetry encompasses methods of image measurement and interpretation in order to derive the shape and location of an object from one or more photographs of that object [12]. The real power of photogrammetry comes from its ability to re-access the wealth of information stored within a photograph, and is a growing component in digital forensic reconstruction work performed today.

The history of photogrammetry dates back to the late 1830's where the process was first found useful in measuring building facades for architectural purposes and military field mapping. The word "photogrammetry" was first coined by Meydenbauer, a German architect, and Kersten, a German geographer, with its first appearance in print dating to 1867 [12]. Numerous instruments have been constructed since then to facilitate the use of this powerful new technology.

The geometric reconstruction of a measured object is the major goal of a photogrammetric process. Except in very few cases, photogrammetric methods are based on the measurement of discrete object points. Geometric elements such as straight lines, planes, cylinders etc. are normally calculated in a post-processing step using the measured 3D points. Computed geometric elements can then either be combined or intersected in order to create additional geometric elements such as the intersection line between two planes. Alternatively, specific dimensions can be derived from them, such as the distance between two points [12] (Figure 03).



*Figure 03. The Photogrammetric Method*

Since digital image processing techniques have become available, the possibilities for photogrammetric image measurement have changed significantly. As in other fields, digital images not only enable new methods for the acquisition, storage, archiving and outputs of images, but most importantly for the automated processing of the images themselves. The two programs used in this paper for image reconstruction, AutoDesk ReCap Photo and Pix4Dmapper, rely exclusively on digital image analysis and both use the pixel coordinate system to define object locations in space.

Every digital image contains a pixel coordinate grid, and each pixel has integer coordinate values. When an object is imaged by a sensor characterized by such a grid, each pixel acquires a grey value corresponding to the local image brightness across its area. Grey values are usually quantized with an 8-bit depth to provide 256 grey color levels ranging from 0 (black) to 255 (white). The 8-bit depth can over range the capabilities of human eye sight, but machines can process much higher levels of detail such as 24 bits per pixel or true color images.

Due to the pixel dimensions and optical transfer characteristics of the digital camera system, an imaged object can cover more than one pixel. This leads to a possible sub-pixel position for the coordinates of the imaged object (Figure 04). Measurements to the sub-pixel level are possible only if the position of an imaged object can be incorporated over several pixels [12].

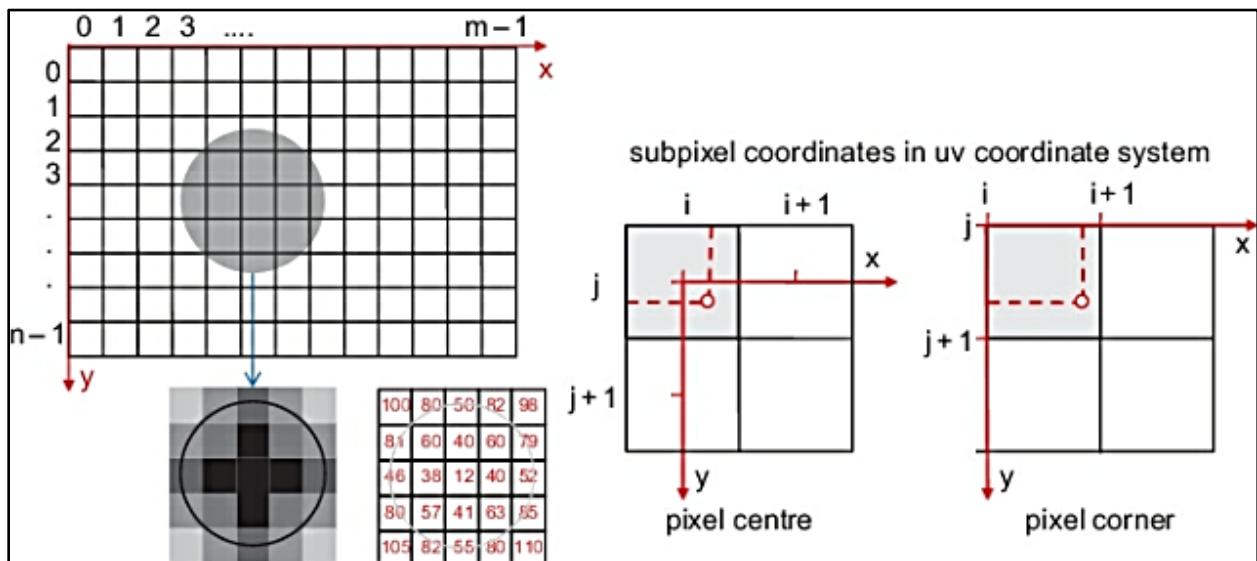


Figure 04. Sub-Pixel Coordinates

The cycle of this photogrammetric process, the reading of discrete object points through the interpretation of quantized digital images, concludes by extending image matching to more than two images. Matched pairs of discrete object points shared between the two clouds are combined in order to fuse single point clouds into a global point cloud. All point clouds are located within one common object coordinate system, and therefore can easily be fused into a single common point cloud.

## CHAPTER III

### METHOD

The processing of 3D scan data involves many steps, this section will navigate through the concepts of capturing, uploading, downloading, and processing of the scan data with each application.

#### Materials

The simulated crime scene: A crime scene is considered as any location that may be associated with an offense that has been committed and where forensic evidence may be gathered [13]. To test the point clouds a simulated crime was developed (Figure 05). Placed in an outdoor setting, this crime scene offers several challenges for each capture technique. The strong lighting contrast, the reflective nature of several of the materials, and the relative size of certain evidence objects will provide the biggest obstacles for thorough capturing, however the low gloss finish of the wall paint and matte finish concrete will also provide a good scanning environment. The windows were eliminated from each point cloud before comparison in method 1 testing because of their highly reflective properties.



*Figure 05. The Overall Crime Scene*



Evidence marker 01 simulates a bullet hole in the wall. This is a small dark and matte colored piece of evidence measuring approximately ½” (Figure 05). For method 2 of the testing, the center of mass of the bullet hole will be used.



*Figure 06. Evidence Marker 1*

Evidence marker 2 is an unused bullet with casing (Figure 07). This object is a small bright and reflective piece of evidence, measuring approximately 1 ½”, with a bright metal reflectance. For method 2 of the testing, the center of mass of the bullet with casing will be used.



*Figure 07. Evidence Marker 2*

Evidence marker 3 is a revolver (Figure 08), which is a medium sized reflective object with dark metal reflectance. For method 2 of the testing, the center of mass will be used to measure the revolvers distance.



*Figure 08. Evidence Marker 3*

Evidence marker 4 represents a muddy foot print and a 12in. metal ruler which be used of our analysis. (Figure 09). This is a medium sized piece of evidence with a bright metal reflectance. For method 2 of the testing, the ruler's overall length will be measured.



*Figure 09. Evidence Marker 4*

Evidence marker 5 represents a body chalk outline (Figure 10). The chalk outline sits partially in direct sunlight and partially in shade which will challenge certain capturing techniques.



*Figure 10. Evidence Marker 5*

Throughout the crime scene fiducial markers were placed to help with the scaling, translation, and rotation of the point clouds. It's recommended that large a visible scale of some type be placed within the captured scene for purposes of accurate scaling (Figure 11).



*Figure 11. Fiducial Marker*

## Capture and Alignment Procedures - EveryPoint Application

EveryPoint is a 3D scanning application available for use on Apple's iPhone 12 Pro. The EveryPoint LiDAR Fusion application utilizes Apple's ARKit (an integrated piece of the A14 Bionic SoC chip) [14], LiDAR, and EveryPoint's photogrammetry algorithms.

The process of capturing is condensed into two settings that the user can adjust before capture, 3D Voxel Size and Max Scanning Depth (Figure 12). The voxel size of a 3D image is equivalent to the pixel resolution in 2D images [15], however the pixel in a 2D image measures height and width, a voxel represents both height and width as well as depth. In a 2D image, smaller pixel sizes contribute to a higher quality image, in voxel terms a smaller voxel size equals a denser and more detailed scan. The Max Scanning Depth refers to the maximum distance the application will take measurements. A 3D voxel size of .5cm, the smallest available, and a Max Scanning Depth of 5m, the farthest available, were chosen.

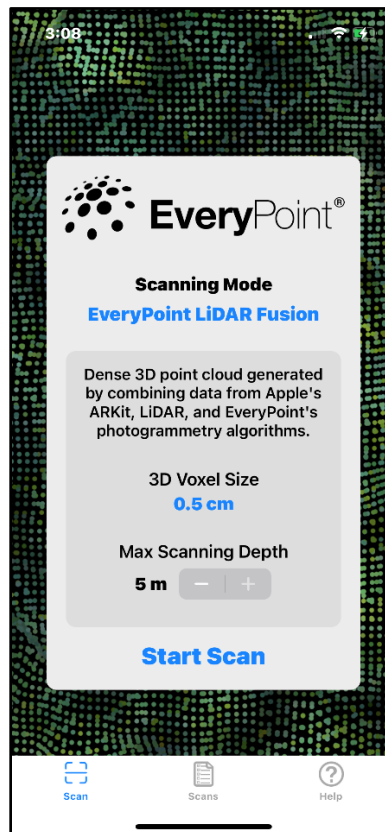


Figure 12. EveryPoint Home Screen



With these settings in place three separate scans were needed to cover the entirety of the scene. Each scan was saved as a .pts file, which is a text file that records the x, y, and z coordinates of each point captured. These .pts files represent the entirety of the point cloud data and can be used by several 3d applications with no further processing necessary, however this papers methodology utilizes the 3D program 3DS Max for point cloud alignment and therefore the .pts file must be converted to a .rcs file format for use within 3DS Max. Once converted the .rcs files are imported into 3DS Max and translated and rotated for best fit within the Faro Focus LiDAR data set. At this point the fiducials would be used as aids in the alignment process, and any translation rotation and scaling of the cloud should be noted (Figure 13).



*Figure 13. EveryPoint Point Cloud Viewed Within 3DS Max*

### **Capture and Alignment Procedures - PolyCam Application**

PolyCam is a 3D scanning software application that was originally launched around the release of the iPhone 12 Pro and iPad Pro, and claims a scan accuracy of down to about 1” [16]. It operates with

a simple user format that requires no setting adjustments before use, however once the scene is captured a processing procedure must take place to create a usable file.

Within the processing settings the user has control of Depth Range, Voxel Size, and Simplification. For this test a maximum depth range of 5m, a voxel size of 9mm, and a simplification (or subsampling) of 0% were selected to create a point cloud with the highest density and farthest range of points that the Polycam app will allow (Figure 14).

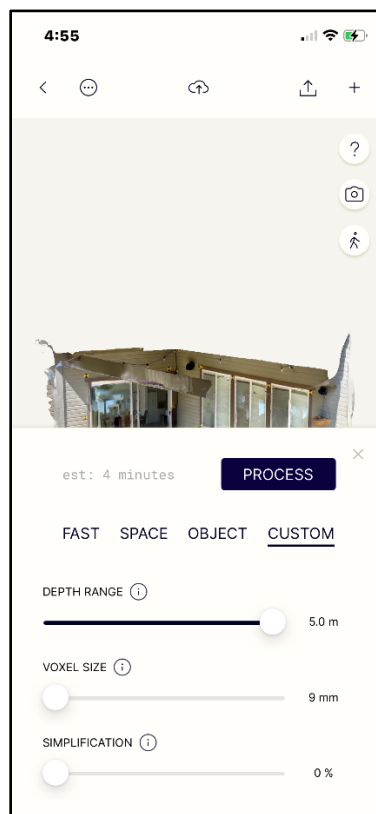
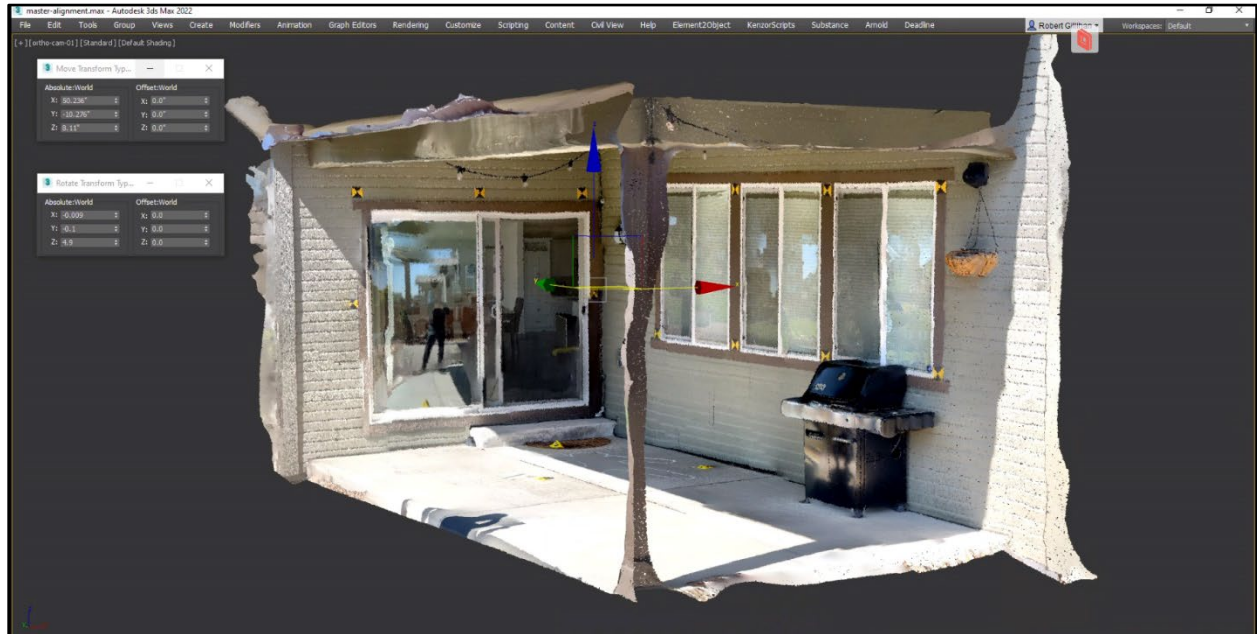


Figure 14. Polycam Custom Process Export Screen

The Polycam app offers several file extensions as exporting options, so a .pts file was chosen as a best fit to work within this methodology's workflow. The entirety of the scene was captured with one pass and exported to a .pts file for processing. As previously explained, a .rcs file is a good fit for use within 3DS Max, so the Polycam's .pts file was converted from .pts to .rcs using CloudCompare and then uploaded into 3DS Max. Once inside 3DS Max the Polycam LiDAR data is translated and rotated for

best fit alignment with the Faro Focus LiDAR data set. At this point the fiducials would be used as aids in the alignment process, and any translation rotation and scaling of the cloud should be noted (Figure 15).



*Figure 15. Polycam Point Cloud with Translation and Rotation Fields Visible*

### **Capture and Alignment Procedures – Faro Focus 3D**

The Faro Focus 3D scanner's point cloud data set represents the base truth measurement for this test. This laser scanner model has a range focus of 0.6m to 120m indoor or outdoor, and a ranging error of  $\pm 2\text{mm}$  at 10m [10]. Six scans were taken of the scene and were registered or placed within the Faro's proprietary software Faro Scene version 2019.2. The registration of the point clouds resulted in a maximum Mean Scan Distribution Error of 2.29mm or .09in, which is considered a green light or acceptable error range. A single .rcs file was created and then exported for use within 3DS Max and a .pts file is created for use within CloudCompare (Figures 16 and 17).

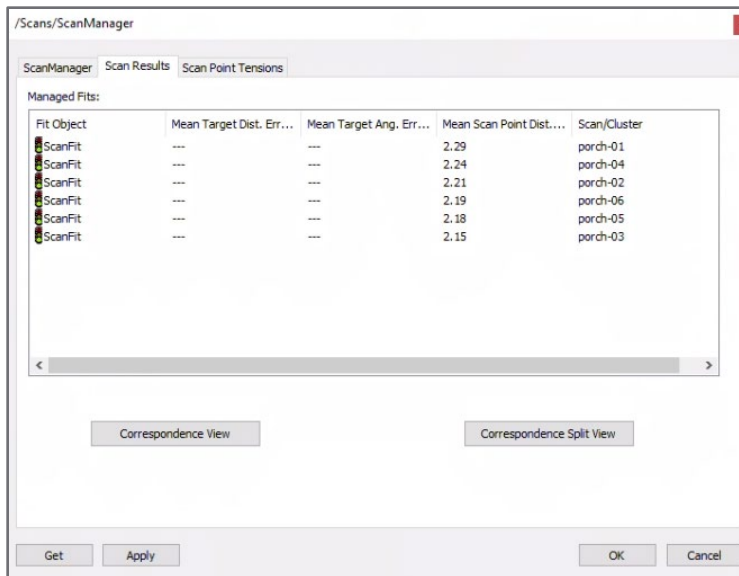


Figure 16. The Faro Focus Point Cloud Scan Placement Results



Figure 17. Faro Focus Point Cloud Viewed Within 3DS Max

## Capture and Alignment Procedures – Photo Capture Using the iPhone 12 Pro

Photo capture using the iPhone 12 Pro's wide camera. A second, and very powerful method of creating a 3-dimensional point cloud data set is available for use with the iPhone. This method utilizes the iPhones ever improving onboard camera. The steps for successfully capturing a sequence of photos



that can be turned into a 3-dimensional point cloud are precise and should be followed for a usable result. Orient the pitch of your camera so that the majority of the image frame is filled with the object that you want to reconstruct and objects that you do not want to reconstruct comprise the minority of the image frame. There is no perfect camera pitch angle. It is also recommended to take an image every 5-10 degrees to ensure enough overlap [17] (Figure 18).



*Figure 18. The Quantity and Positioning of Each Photo*

### **Processing Photos – AutoDesk ReCap Photo**

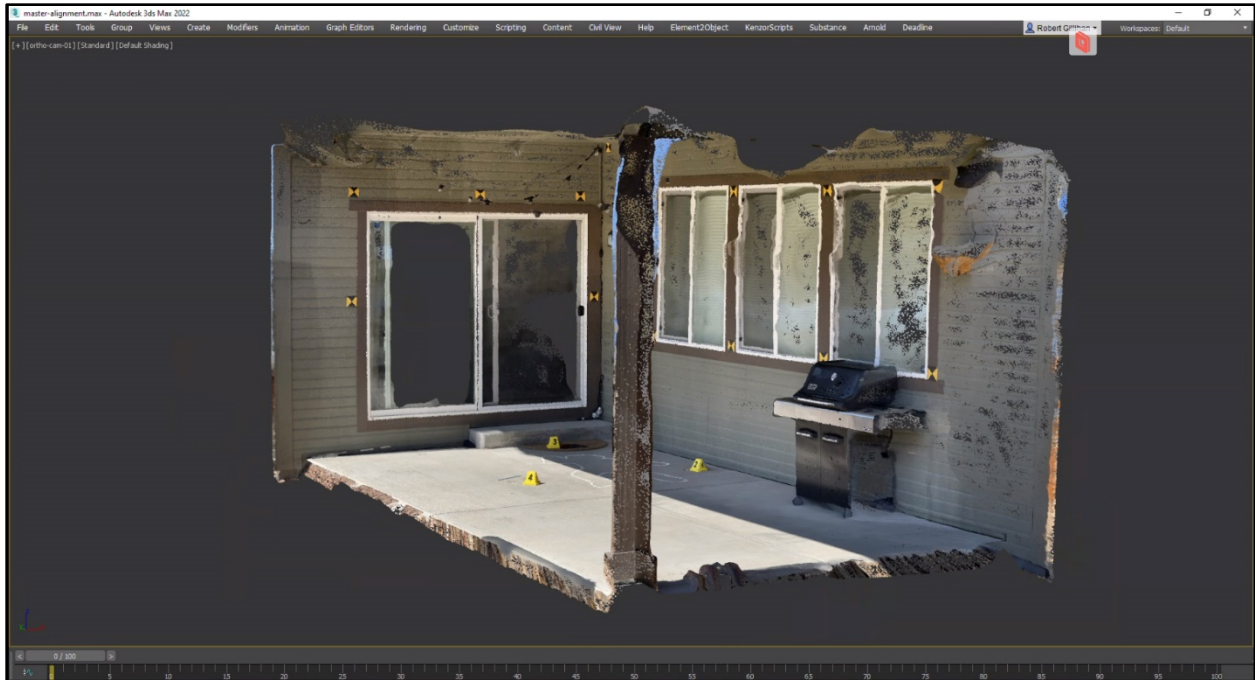
AutoDesk Recap Photo is an image-based photogrammetry software application launched in 2013, the version used in this testing is the most current update to the software, version 22.1.

Users can import up to 300 digital images captured from a wide variety of cameras. ReCap Photo claims an accuracy of up to  $\pm 1$  pixel of the input images [18]. According to AutoDesk, the ReCap application is capable of identifying lens distortion in the submitted digital images, removing it, and processing the distortion free images into a 3D point cloud [19]. Although not specifically mentioned,

it's assumed that the best results would generate with images containing their original metadata which allows the program to identify the camera's make and model and facilitates the distortion removal.

The Recap program offers a simple user interface which asks the user to drag and drop images into a newly created project and simply start the processing. The lack of input makes it easy to generate a result but relies on the user's ability to take a quantity and quality of photos suitable for point cloud generation. To reconstruct a 3D object using photos will require you to have a minimum of 20 photos in .JPG format. These photos should be taken in as short a time as possible and encompass the entire object you wish to convert, the light sources must remain consistent from photo to photo, and you should avoid casting shadows onto the object during the process of photographing it [20].

The program allows the user to select their ideal output format, which for purposes of this methodology the .rcs, an AutoDesk ReCap Scans file format, was saved and loaded into 3DS Max for translation and scaling (Figure 19). It's crucial to understand that re-scaling of the point cloud data must be conducted with image based photoscanned objects, and a large visible distance scale must be incorporated into the scene to determine a universal scale amount. For this experiment we use the Faro Focus scan data as a base truth, which is much better at automatically determining a correct scale factor before creating data files. For this reason, I was able skip adding a scale to my simulated crime scene and in its place use a variety of fiducial markers placed throughout the scene to universally scale the point cloud (scaling in all x, y and z axes equally) until the fiducial markers align with the Faro scans fiducials. This scale factor is noted, along with x, y and z translation amounts.



*Figure 19. ReCap Point Cloud Viewed Within 3DS Max*

### **Processing Photos – Pix4Dmapper**

Pix4d launched in 2011 and boasts a  $\pm 1$  pixel range of accuracy. Much like the AutoDesk ReCap Photo application Pix4Dmapper is able to load a series of digital images and using photogrammetry will produce a point cloud data set.

Pix4D automatically finds thousands of common discrete object points between images. Each characteristic point found in an image is called a keypoint. When 2 keypoints on two different images are found to be the same, they become matched keypoints. Each group of correctly matched keypoints will generate one 3D point. When there is high overlap between 2 images, the common area captured is larger and more keypoints can be matched together [21].

The Pix4Dmapper user interface is more robust with more variable input than the AutoDesk ReCap Photos simple drag and drop approach. All images, are loaded into the program and assigned a custom Geolocation Accuracy setting by adjusting the Accuracy Horz [m] to 0.10 and the Accuracy Vert [m] to 0.20, based on the results and the quality control report generated after processing these setting could be adjusted. The output coordinate system should be adjusted to feet with a Known Coordinate

System generating based on the iPhone images metadata. Under Initial Processing the Free Flight or Terrestrial option should be selected and the Initial Processing of the data should begin. Based on the quality report generated after the Initial Processing (Figure 20) the user could adjust the accuracy setting mentioned above or proceed to output the Point Cloud and Mesh.

The examination of the quality report reveals an acceptable level of images with 20,991 keypoints found per image, >10,000 keypoints is considered acceptable. A caution that only 584 out of 708 images calibrated which is a result of photographs not properly overlapping, photos that captured too much sky and not enough building, or the most likely culprit, photos with reflection on several of the large windows (the windows glass will later be removed from the scan data so it is appropriate to proceed). Camera optimization looks at the percentage of the difference between the initial and optimized focal length for a perspective lens, and our 1.89% falls well within the 5% or below threshold as an acceptable score. The Matching check score of 1,736.48 sits well above the minimum of 1,000 matches per calibrated image need to earn an acceptable score. The Georeferencing check will be ignored as no 3D GCP's were used in the scene.

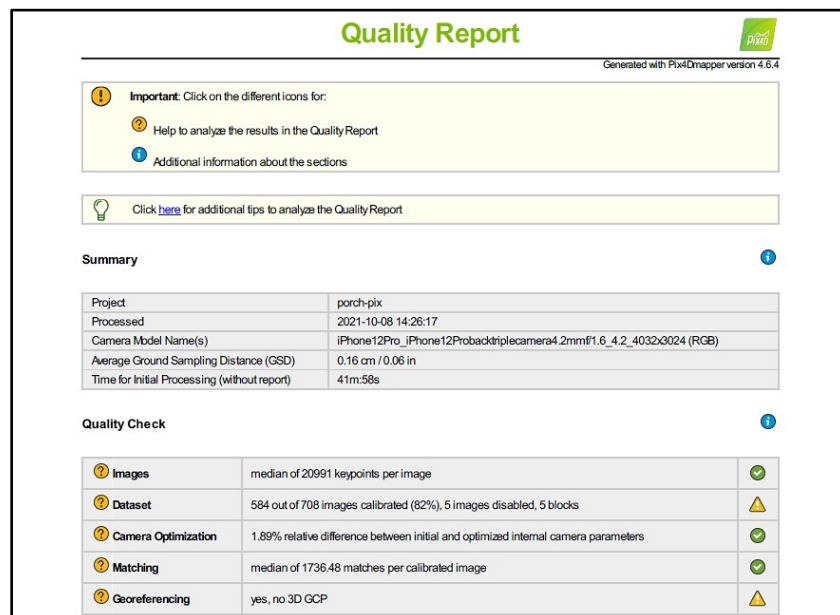
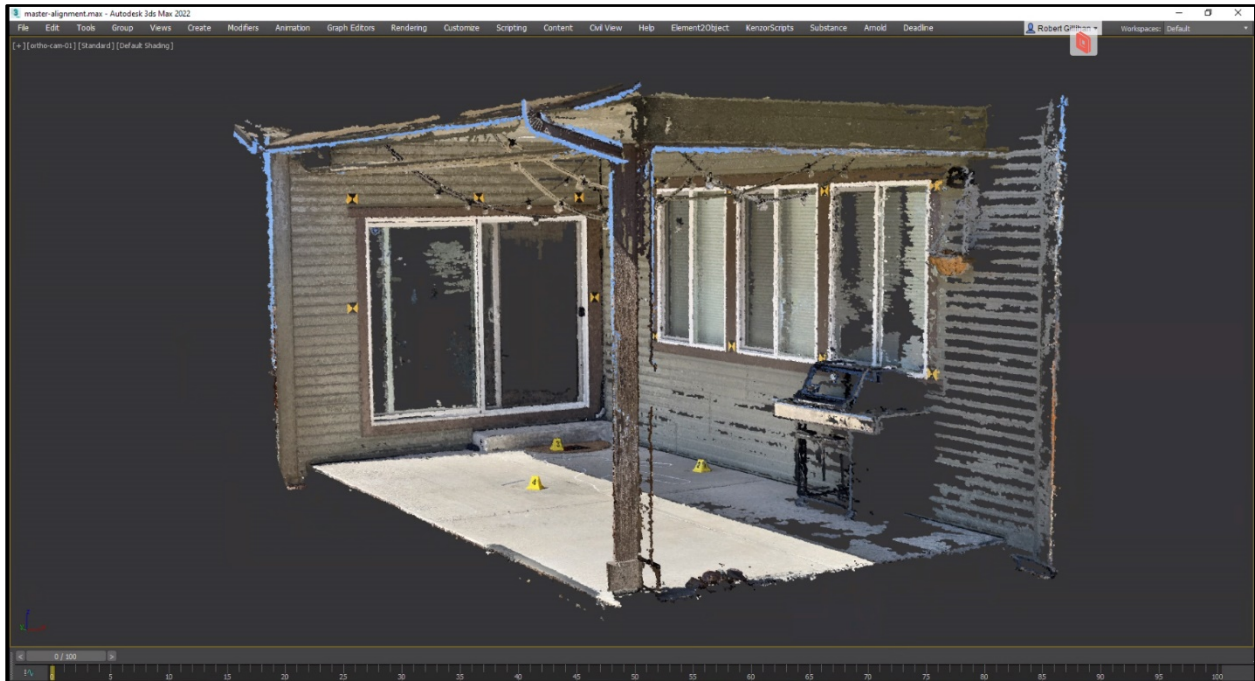


Figure 20. Pix4dmapper Quality Report

The only input change made during the Point Cloud and Mesh process was the selection of a .las file type as the export file type, all other settings remain at default. Once created the .las file was

converted to a .res file format for transfer to 3DS Max for scaling and translation adjustment to the Faro Focus benchmark scan (Figure 21).



*Figure 21. Pix4dmapper Point Cloud Data Set Displayed Within 3DS Max*

### **Using 3DS Max**

3DS Max is software designed for 3-dimensional modeling, animation, rendering, visualization, and is capable of translating and rotating objects with increments as small as 1,000<sup>th</sup> of an inch [22]. It offers an ideal workspace to quickly view, translate, and scale our point clouds for best alignment and subsequent comparison within the CloudCompare software program. The benchmark Faro Focus scan is our first data set to be imported and placed. All other data sets from our testing were imported, aligned, and scaled to this benchmark scan (Figure 22). Once aligned, the translation, rotation, and scale factor parameters of each scan are noted and used to accurately recreate this alignment inside of CloudCompare for further analysis. 3DS Max also offers measuring tools which were used to create the right-angle distance measurements between the various objects located in the scene.



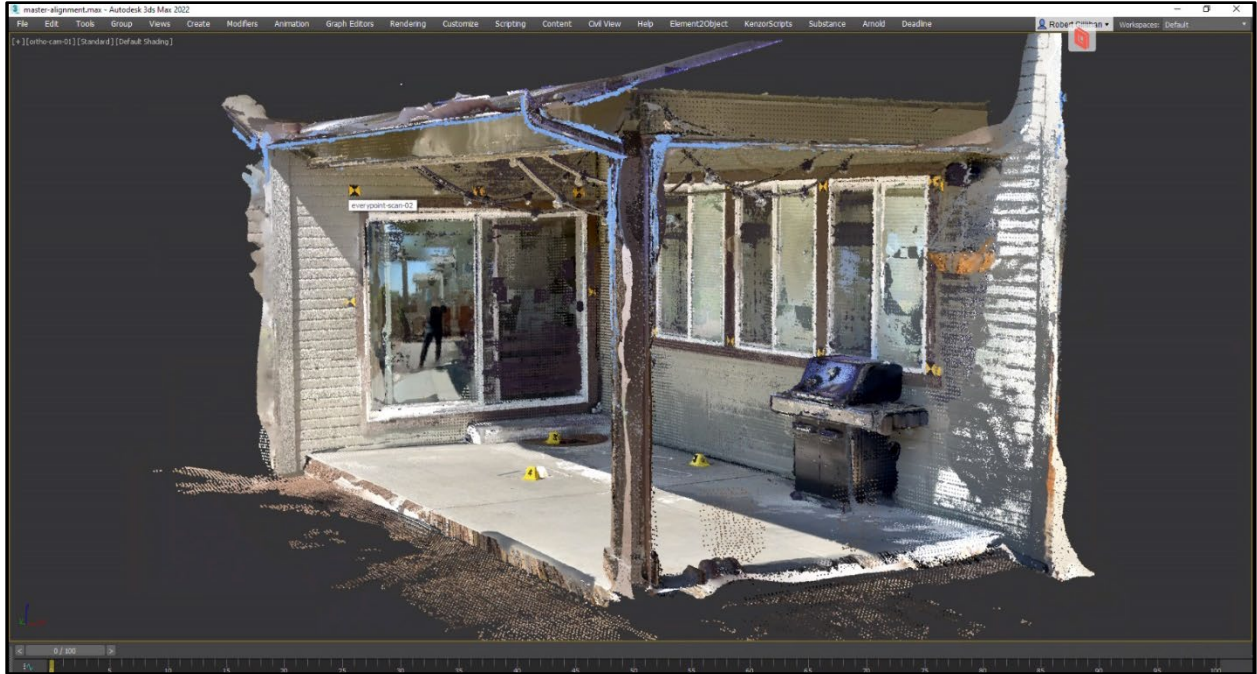


Figure 22. All 5 Scan Sets Aligned and Overlaid Within 3DS Max

### Using CloudCompare

CloudCompare is a 3D point cloud (and triangular mesh) processing software. It was originally designed to perform comparisons between two dense 3D points clouds, but has expanded its useability to become a more general point cloud processing software. This experiment utilized CloudCompare's original core functionality, to provide an accuracy comparison between two sets of point cloud data, our benchmark Faro Focus point cloud and the four tested clouds (Figure 23).

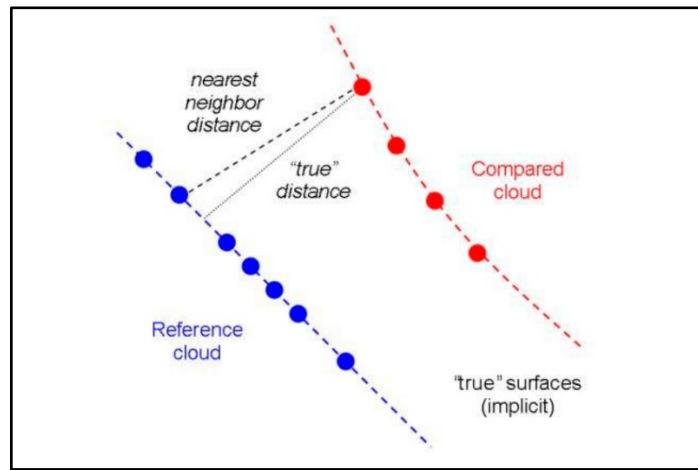


Figure 23. Example of CloudCompare's Compute Cloud Distance Tool and Reference Order for Each Data Set

The process starts by importing each point cloud data set into the program. Each data set has been translated, rotated, and scaled within 3DS Max and each of these changes needs to be repeated within the CloudCompare software using the apply transformations tool. After transformations are applied each point cloud is cloned and the few remaining steps will be administered to the cloned clouds (Figure 24).

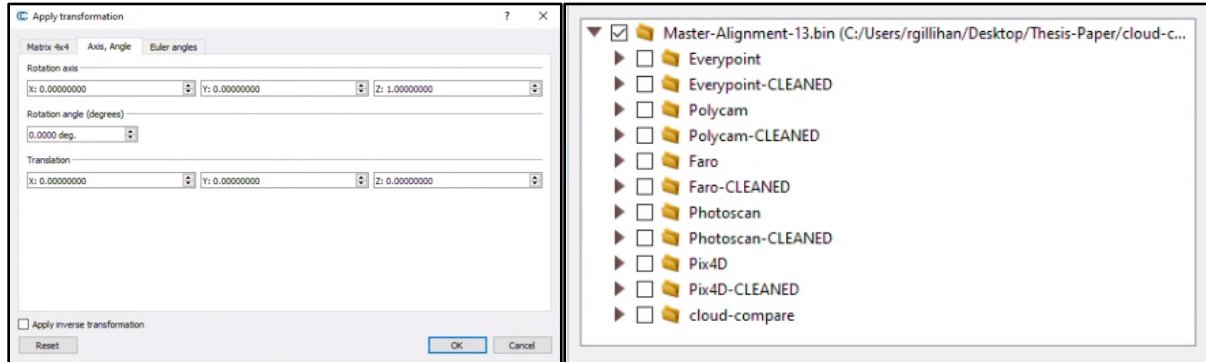


Figure 24. Example of CloudCompare's Apply Transformation Tool, and File Structure Organization

CloudCompare offers the ability to trim or clean a point cloud, so for the sake of comparison all reflective window surfaces were removed from each cloud. To initiate the comparison the “compute cloud / cloud distance” tool was used which involves selecting our Faro scan and the cleaned scan from each testing set.

The Faro scan is used as the Reference data set and each tested cloud will be used as the Compared data set (Figure 25). When the Cloud/Cloud distance computation dialog appears, CloudCompare will first compute approximate distances (which are used internally to automatically set the best octree level at which to perform the real distances computation). The reference cloud is hidden and the compared cloud is colored with those approximate distances [23].

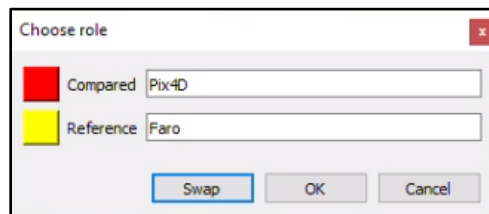


Figure 25. Example of CloudCompare's Compute Cloud Distance Tool and Reference Order for Each Data Set

## CHAPTER IV

### RESULTS

Three testing methodologies were used to evaluate the results, method one was cloud to cloud comparison measuring point to point distance, method two is a distance measurement comparison between various objects in the simulated crime scene, and method three observes the clarity and positional accuracy of a chalk outline.

#### **Method 01: Cloud to Cloud Comparison**

Method one was cloud to cloud comparison measuring point to point distance [24]. The results from CloudCompare cloud distance tool's absolute distance measurements: EveryPoint had 89% of captured points aligned to within 1" of the Faro 3D scan, Polycam had 62% of its points fall to within 1", Recap Photo had 78% of points fall to within 1", and Pix4dmapper had 90% of points fall to within 1" of the Faro 3D scan. Using Figure 26 as an example, we can determine that our EveryPoint data set contains 180,025 points or voxels which is a low density compared to the pixel count of the Faro at 16,619,610 points. The graph is split into 256 classes of length from left to right. These classes gather and register all points whose error distance falls within their range and places a dot on the graph, the higher the dot the more points gathered at that distance. Looking at Table 01, we see that EveryPoint's data set has a large majority of its points, 89%, fall within 1" or .025m. We can also see that no more than a hand full of points fall outside of 1.50" in distance, and a large spike of points at the end that fall outside of the graphs .0635m or 2.5" error range. These points would be considered trimming errors and boundary errors and could be cleaned to zero to accurately match. Accompanying the chart is a visualization of the cloud with the same color-coated error range printed on the right hand of the graphic, (Figure 26).



Table 01. Cloud to Cloud Comparison (EveryPoint vs Faro)

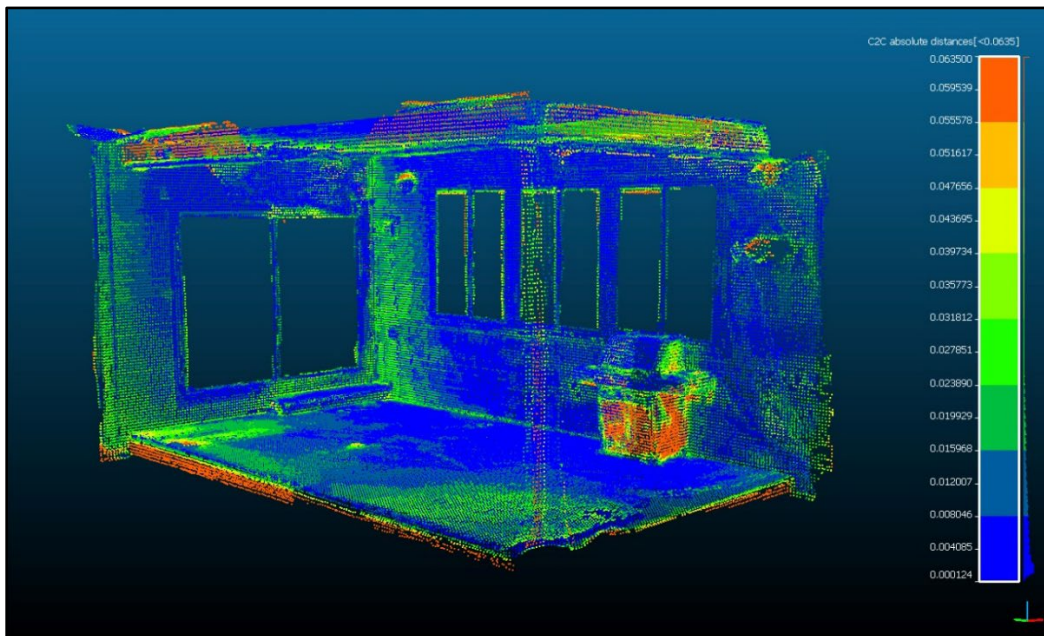
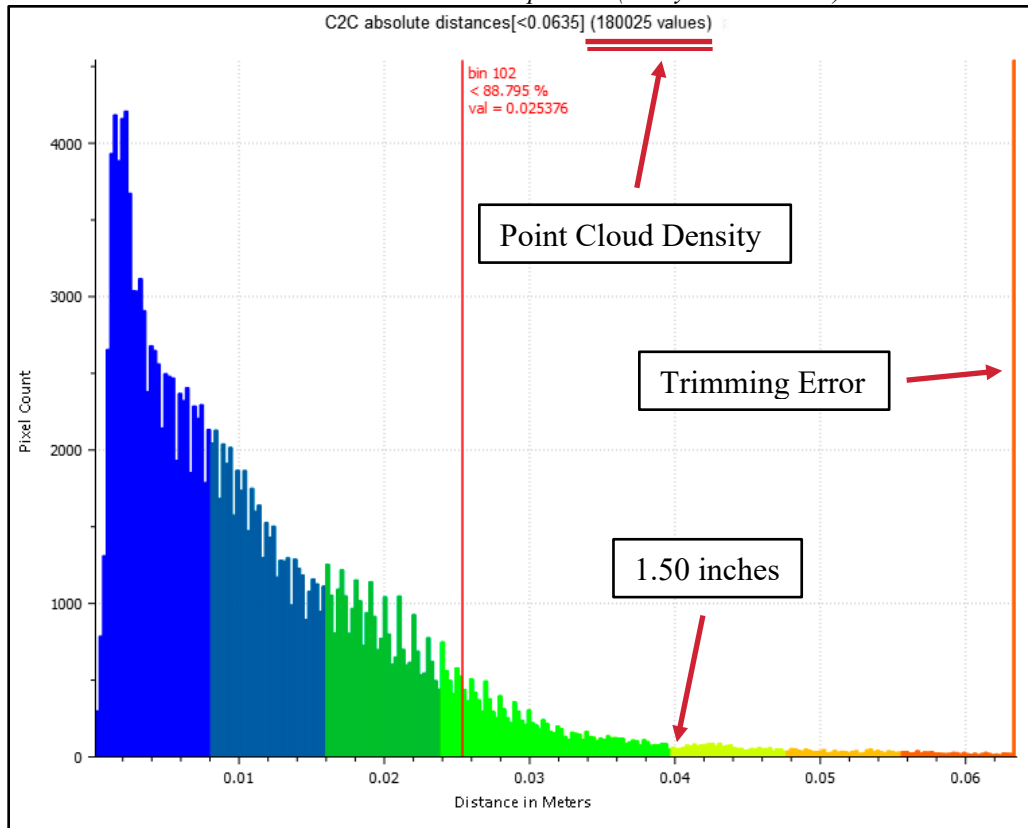


Figure 26. Cloud to Cloud Comparison (EveryPoint vs Faro)

## Method 02: Distance Measurement

Method two is a distance measurement comparison between various objects in the simulated crime scene. Each object was measured from inside 3DS Max using the tape tool. An exact right angle was drawn from the base of the porch step or exterior walls to the center of mass of objects labeled with Evidence Markers #1 thru #3. For Evidence Marker #4, a 12-inch ruler, a single measurement was taken to determine overall length. These measurements are compared to measurements taken from the Faro 3D Scanner (Figure 27).

Measurements of the Difference in Total Distance and Standard Deviation Distance are calculated (Table 02). The Total Distance statistic helps to understand just how far off in measurement your cumulative scene calculation would be. A Standard Deviation calculation helps to understand how wide a collection of numbers vary around their average. The equation for Standard Deviation takes the square of the subtracted mean from each value then sums and multiplies by 1 over the number of values, then takes

the square root of that value to get the Standard Deviation

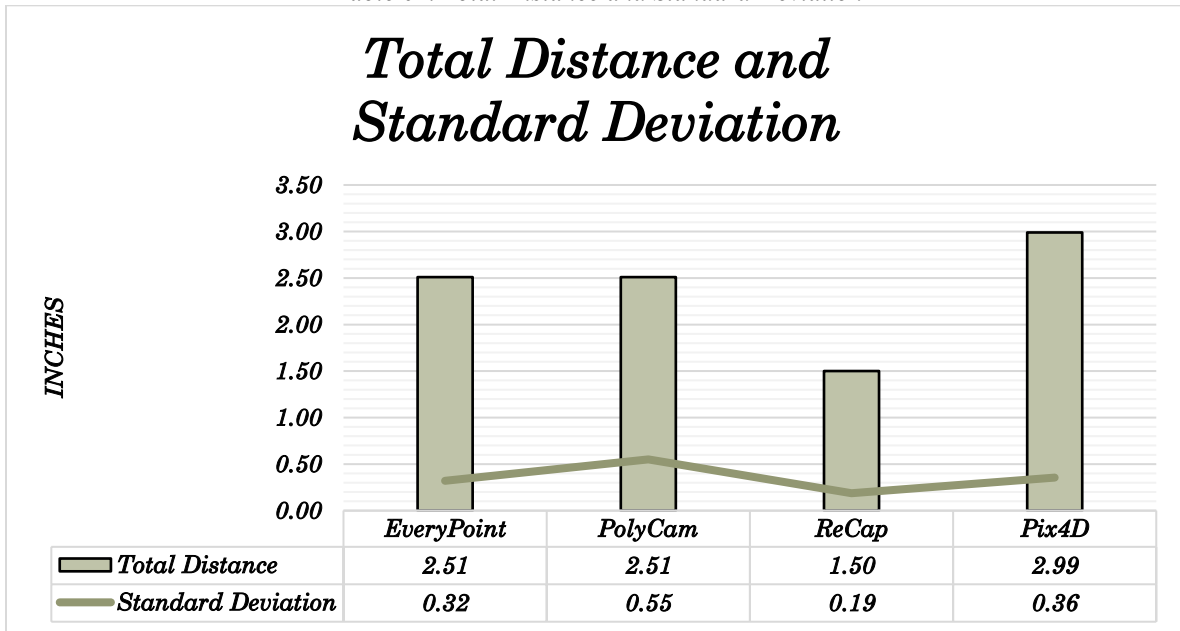
$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2}$$

All of these measurements are dependent on the density and clarity of the scanned objects point cloud. For less dense point clouds, like the Everypoint data set, measurements were unattainable for Evidence Marker's #1, #2 and #4.



Figure 27. Distance Measurements for the Pix4D Point Cloud

Table 02. Total Distance and Standard Deviation



### Method 03: Point Cloud Clarity

Method three was designed to look at accuracy and clarity of the point cloud by visually observing the body outline scribed to the concrete floor using chalk. The data sets were aligned and



scaled for best fit to the Faro point cloud within 3DS Max. The chalk outline is positioned roughly half in half out of shadowing which presents a challenging contrast issue for laser scanning as seen in the results (Figure 28).



*Figure 28. Polycam Chalk Outline*



*Figure 29. ReCap Chalk Outline*

It is the photogrammetry produced cloud creations that performs well on this test with the camera of the iPhone able to handle the sharp contrast of shadow and light and present a full picture of the outline (Figure 29). To compare, within 3DS Max a spline was 3D snapped on top of each point cloud tracing the outline. By setting up a single fixed position orthographic camera [19] within 3DS Max, as illustrated

in Figure 30, the outlines can be laid one on top of another and overlaid with a 6" x 6" grid for comparison, (Figure 31).

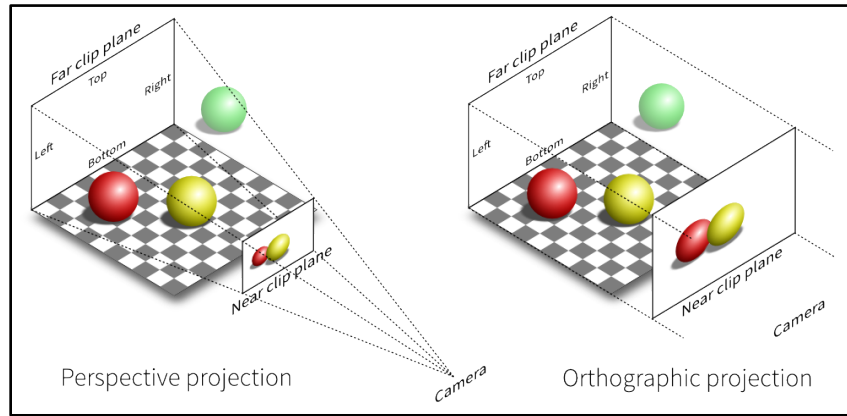


Figure 30. Orthographic Projection vs Perspective Projection

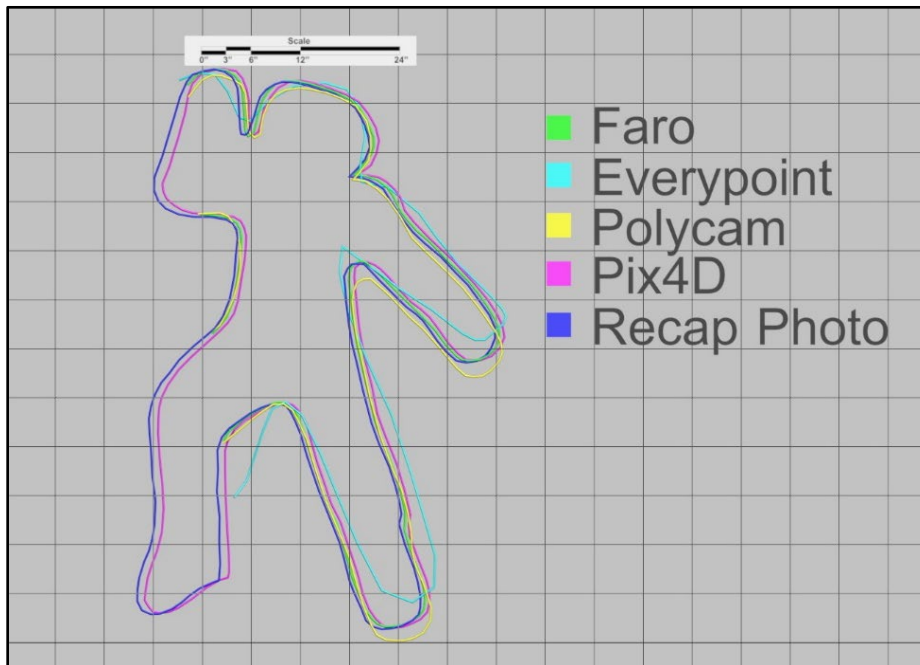


Figure 31. All Chalk Outlines Overlaid on top of 6" x 6" Grid

## **CHAPTER V**

### **CONCLUSIONS**

#### **Discussions**

In the introductory chapter of this paper a question was raised, would more thorough collections of 3D data become common if investigators had access to devices and techniques that would make this task less costly, more efficient, and just as accurate. This paper advanced the idea that two methodologies are available, from an affordable device, for every investigation that would support the collection of such data.

Each methodology and application of point cloud capture and creation was successful, and would only sever to benefit an investigation by offering at minimum a general overall 3D image of the crime scene with reasonable accuracies when compared to a precision laser scanner. In certain circumstances millimeter precision of a point cloud would be required and the iPhone's data set might not be the best tool, however in a situation were no data of this type would otherwise be collected the iPhone's data should be trusted with a reasonable level of confidence.

The iPhone's lidar capturing capability is powerful, accurate, and offers the investigator the quickest method of 3D data acquisition. However, it must be noted that each capture of the scene is variable depending on the care taken by the user. The results of this papers data analysis suggest that the best method for 3D data acquisition using the iPhone resides in the collection of overlapping photographs that can be photogrammetrically combined. This methodology has several advantages, it's quick to perform, it takes advantage of the iPhones substantial image creation system to produce data in a high contrast situation, and its accuracy outperforms the iPhones lidar capturing technique. Perhaps complementing this photo capture technique with the lidar scan technique and obtaining two sets of point cloud data would be a great solution for any investigation.

## Future Research

The testing performed for this paper leaves room for several testing techniques that were not addressed. Careful consideration was given to each method of analysis but in the end only so many methods and variations can be evaluated. In this section I will discuss several options for future research that would benefit the results found in this study.

In the Method 01 analysis I chose four separate software applications to evaluate performance and accuracy but they are just four of a vast many when it comes to LiDAR applications for the iPhone and Photogrammetry software for the desktop. For future research several additional software applications could be chosen.

In the Method 02 analysis a single individual was tasked with determining the center of mass, a crucial evaluation for the larger objects. For future research a survey type evaluation of ten people for example placing the measuring tool according to their judgement might prove substantial.

In the Method 03 analysis a chalk outline was re-traced by relying on each data sets density and clarity for an accurate result. In future research perhaps individual items scanned as part of a scene could be isolated or cut out of the overall scan and point cloud density could be observed on an item-by-item basis.

Finally, for the scene itself I chose partially enclosed outdoor setting which leaves room for trimming error. While each data set was trimmed to the best of my ability it did leave room for a small amount of this error type. To eliminate this in future research perhaps an indoor space with well-defined borders would eliminate some, if not all of that trimming error.

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# APPENDIX

## Method 01: Cloud to Cloud Comparison Results

Table 03. Cloud to Cloud Comparison (Polycam vs Faro)

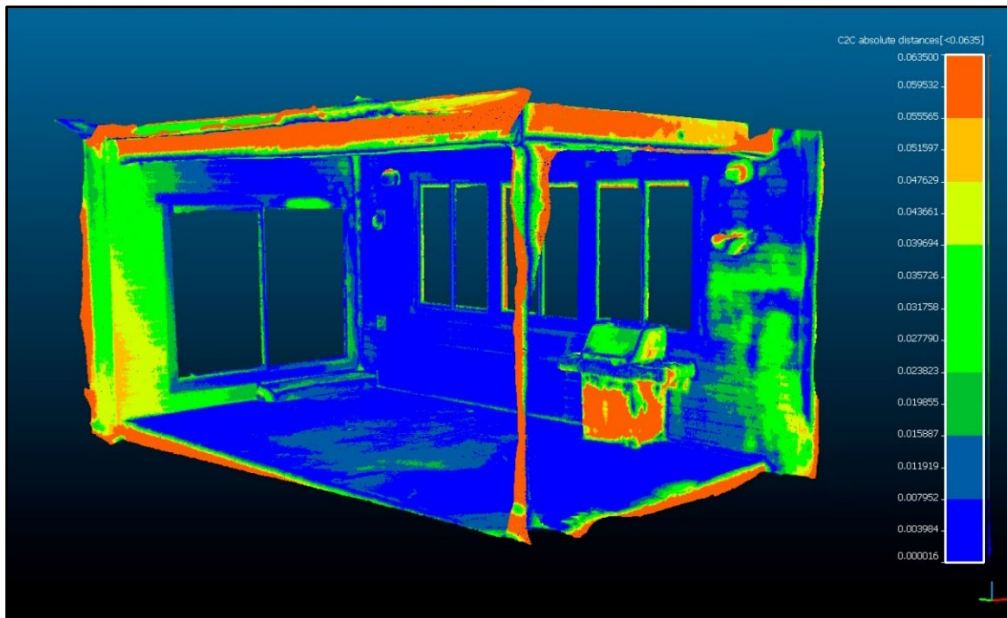
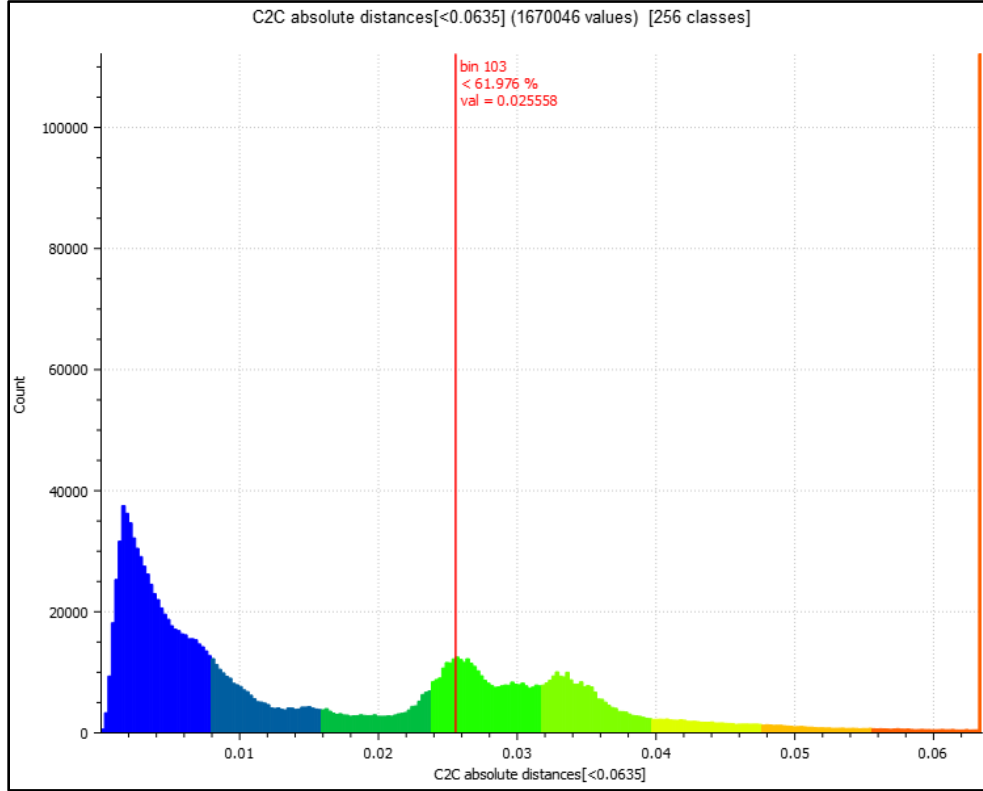


Figure 32. Cloud to Cloud Comparison (Polycam vs Faro)

Table 04. Cloud to Cloud Comparison (ReCap vs Faro)

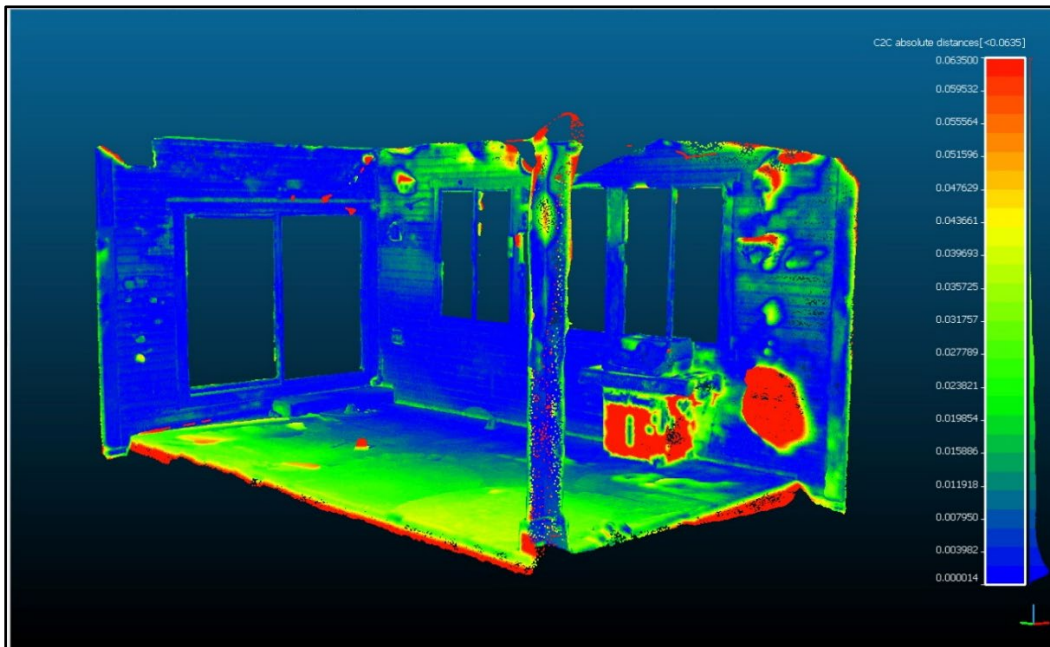
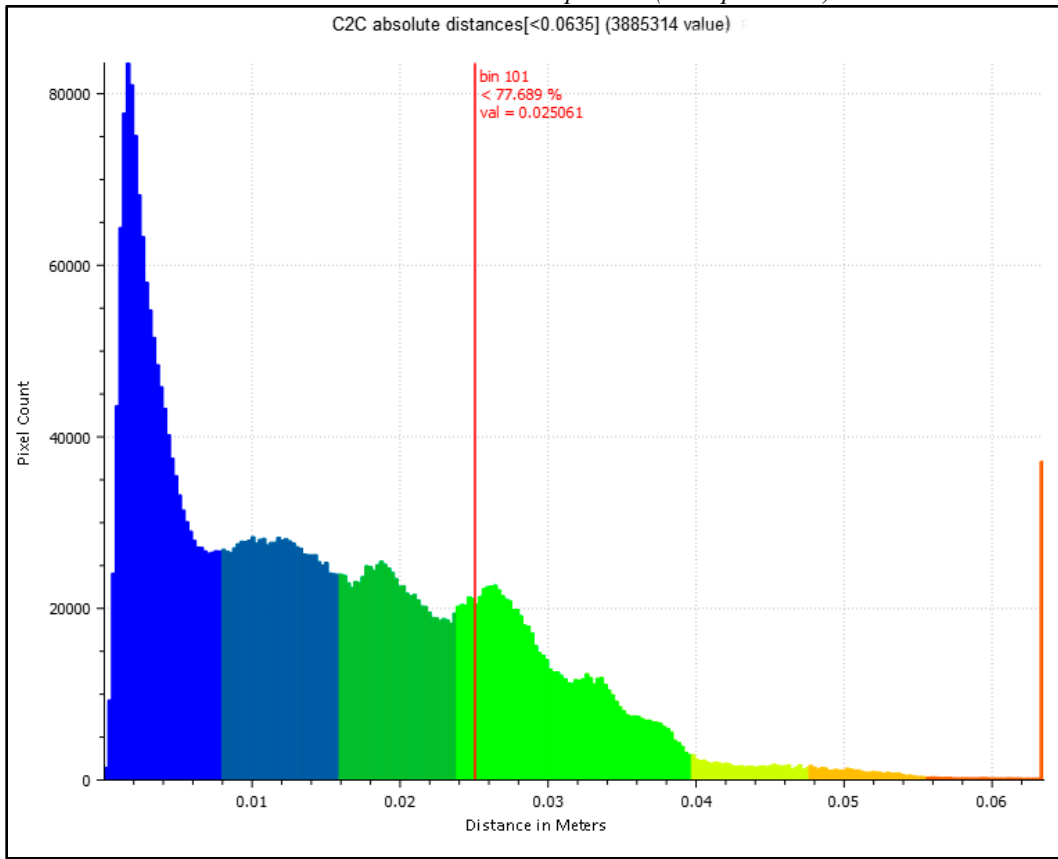


Figure 33. Cloud to Cloud Comparison (ReCap Photo vs Faro)

Table 05. Cloud to Cloud Comparison (Pix4Dmapper vs Faro)

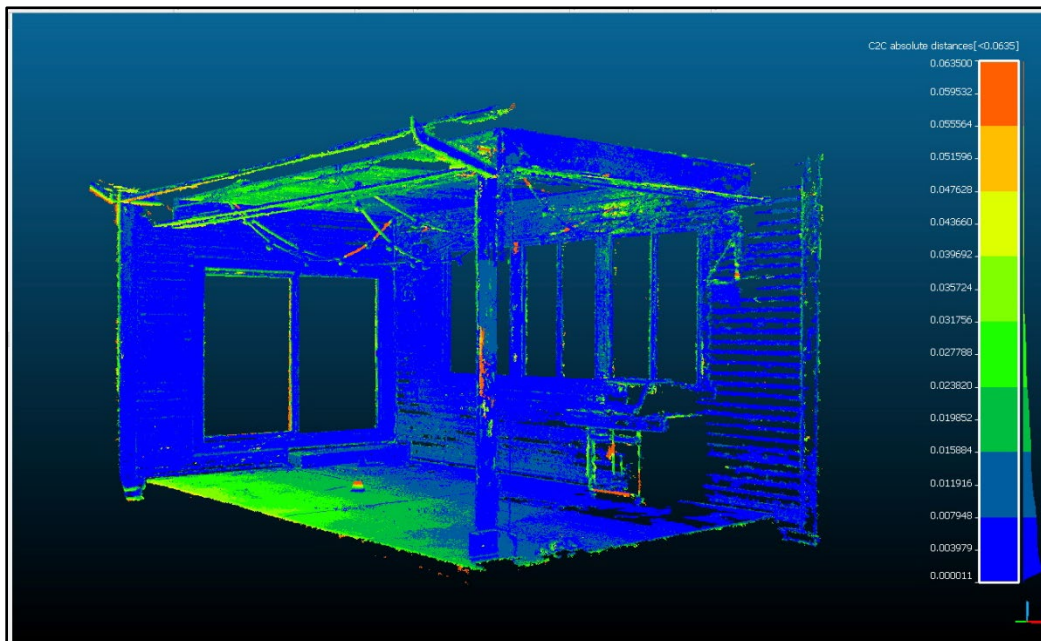
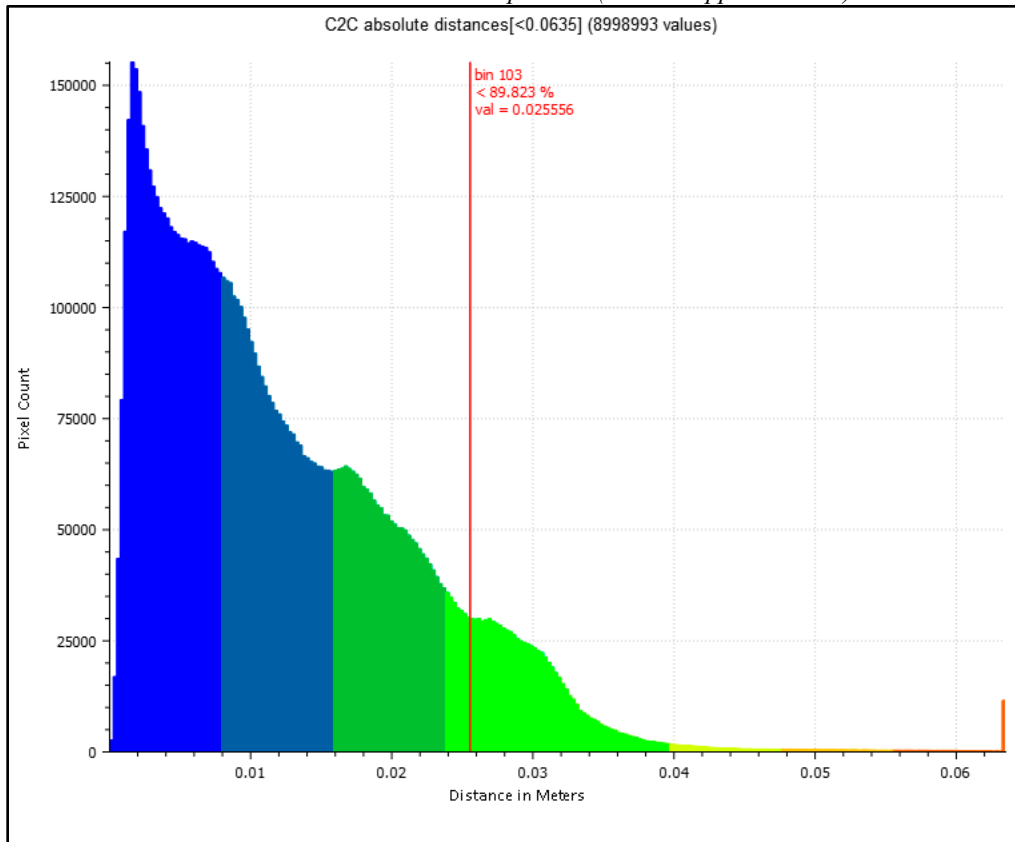


Figure 34. Cloud to Cloud Comparison (Pix4Dmapper vs Faro)



## Method 02: Distance Measurement Results



Figure 35. Distance Measurements for the Everypoint Point Cloud



Figure 36. Distance Measurements for the Polycam Point Cloud

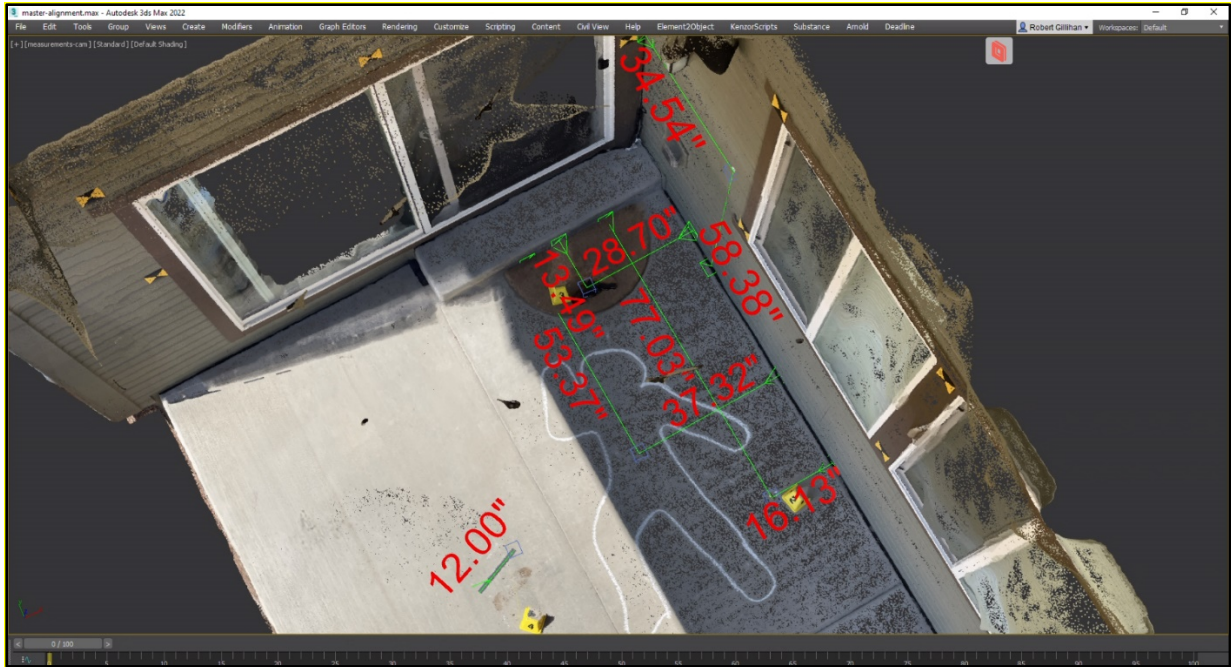


Figure 37. Distance Measurements for the ReCap Point Cloud



Figure 38. Distance Measurements for the Faro 3D Scanner Point Cloud

Table 06. Total Distance Measurements Evidence Marker #01

<b>Total Distance Measurement Inches</b>			
<b>Evidence Marker 01</b>			
	<b>X Axis</b>	<b>Y Axis</b>	<b>Z Axis</b>
<b>EveryPoint</b>		n/a	n/a
<b>PolyCam</b>		34.25	58.12
<b>ReCap</b>		34.54	58.38
<b>Pix4D</b>		35.21	58.76
<b>Faro</b>		35.02	58.33

Table 07. Total Distance Measurements Evidence Marker #02

<b>Total Distance Measurement Inches</b>			
<b>Evidence Marker 02</b>			
	<b>X Axis</b>	<b>Y Axis</b>	<b>Z Axis</b>
<b>EveryPoint</b>	n/a	n/a	
<b>PolyCam</b>	15.22	78.69	
<b>ReCap</b>	16.13	77.03	
<b>Pix4D</b>	16.53	76.78	
<b>Faro</b>	16.04	76.88	

Table 08. Total Distance Measurements Evidence Marker #03

<b>Total Distance Measurement Inches</b>			
<b>Evidence Marker 03</b>			
	<b>X Axis</b>	<b>Y Axis</b>	<b>Z Axis</b>
<b>EveryPoint</b>	27.93	13.22	
<b>PolyCam</b>	29.93	13.5	
<b>ReCap</b>	28.7	13.49	
<b>Pix4D</b>	29.99	13.55	
<b>Faro</b>	29.02	13.59	



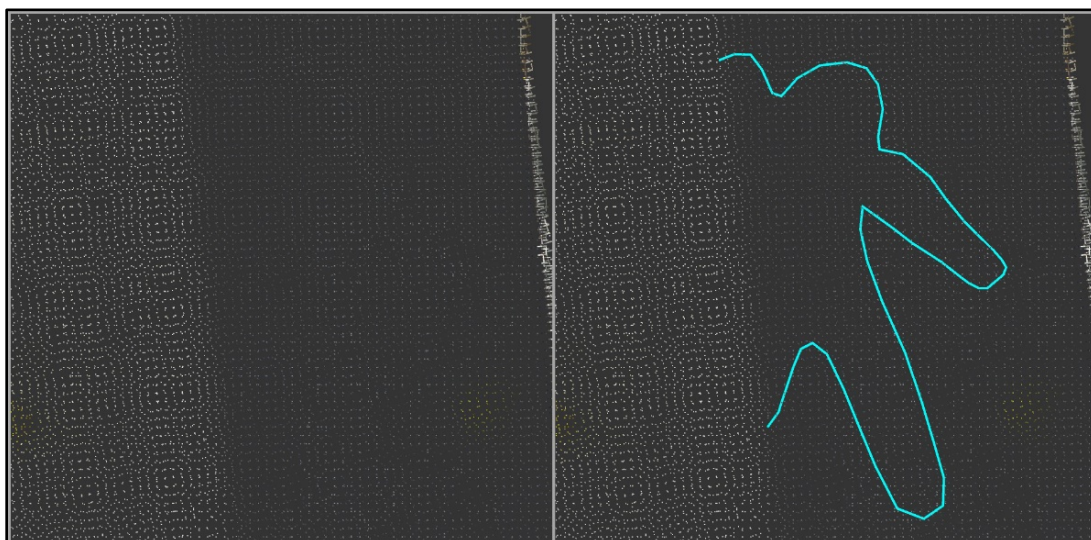
Table 09. Total Distance Measurements Evidence Marker #04

<b>Total Distance Measurement Inches</b>			
<b>Evidence Marker 04</b>			
	<b>Total Length</b>		
<b>EveryPoint</b>	n/a		
<b>PolyCam</b>	11.52		
<b>ReCap</b>	12		
<b>Pix4D</b>	12		
<b>Faro</b>	12		

Table 10. Total Distance Measurements Evidence Marker #05

<b>Total Distance Measurement Inches</b>			
<b>Evidence Marker 05</b>			
	<b>X Axis</b>	<b>Y Axis</b>	<b>Z Axis</b>
<b>EveryPoint</b>	37.21	53.27	
<b>PolyCam</b>	37.68	53.05	
<b>ReCap</b>	37.32	53.37	
<b>Pix4D</b>	38.44	53.86	
<b>Faro</b>	37.67	53.86	

### Method 03: Point Cloud Clarity Results



*Figure 39. EveryPoint Chalk Outline*



*Figure 40. Pix4D Chalk Outline*



*Figure 41. Faro Chalk Outline*