CONNECTING THE DOTS: CHOOSING AN APPROPRIATE TERRESTRIAL LASER SCANNING HARDWARE AND SOFTWARE SYSTEM TO DOCUMENT THREE EARLY 20TH CENTURY BUILDINGS ON THE CAMPUS OF TEXAS A&M UNIVERSITY

A Thesis

by

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ABSTRACT

The use of three dimensional laser scanning systems in creating high quality documentation of cultural heritage sites and structures in the form of point cloud data sets has become common practice in recent decades as the technology has advanced. As with many other technologies users often make the assumption that the newest, or latest, model is always best suited for the job at hand. Utilizing three historic buildings from the early 20th century that are located on the main campus of Texas A&M University this study questions that assumption by conducting a comparative analysis of data sets collected by three terrestrial laser scanning hardware systems that have been released in recent years by a single manufacturer (FARO Technologies) with the objective of determining if there are significant observable differences in the resulting point cloud data sets when all of the data sets are processed and registered by the same software program (FARO SCENE 2018.0.0.648). Through the visual assessment of each point cloud in the study, the analysis of empirical data in the form of registration reports provided by the software, and calculated differences of selected measurements within the point cloud data, this study indicates that there is no significant difference in the consistency of the resulting point cloud data sets based on the age and model of the hardware system being utilized in collecting the data as long as the data sets are processed using a recent version of an appropriate software program.

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CONTRIBUTORS AND FUNDING SOURCES

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The data gathered during the summer of 2015 was collected by a research team consisting of students enrolled in ARCH 485-102, a 5-week, 3-credit, Directed Study course focusing on the recording of historic buildings. The research team was led by the researcher, under the supervision of Prof. Robert Warden. The rest of work conducted for the thesis was completed by the researcher.

The laser scanning hardware and software used in this study are the property of the Center for Heritage Conservation (CHC) which is a part of the College of Architecture at Texas A&M University. No funding sources were utilized in the completion of this study.

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1. INTRODUCTION

1.1. Background and Significance

As predicted in 1965 by Gordon Moore, co-founder of Intel, the number of transistors on a single computer chip have been doubling at regular intervals. Moore's original prediction of a 12 month interval, later amended in 1975 to a 24 month interval, is known today as Moore's Law.[1] Due to this consistent advancement in computer chip technology, we see a similar exponential rate of innovation and change in regards to computing power, and in turn the technologies that utilize that computing power. One technology that has benefited from these advancements is three dimensional (3D) laser scanning.

The utilization of three dimensional scanning data has become common in many industries today; however, that was not always the case. When first introduced the 1960's, the original models of three dimensional scanners had considerable limitations in regards to the method of use and speed of the process.[2] Despite using many of the same basic technologies found in the three dimensional scanners available today, such as cameras and a form of projected light, these limitations, in combination with the lack of widespread computing capabilities and resources at the time, meant that three dimensional scanning was slow to advance, both in terms of technological ability and accepted use as a viable tool in accurately documenting heritage sites. But all of that would change in 1985 with the availability of white light sources and lasers that could be used in the scanners to speed up the process. This particular advancement, the utilization of lasers, in combination with the exponential growth in personal computing over the last 20+ years due to Moore's Law, have led to the development of what we know today as three dimensional laser scanners.[3]

With a growing global market, valued at just under $2 billion (USD) in 2017, the three dimensional laser scanning industry is here to stay. Leading analytics companies, like Transparency Market Research, predict that number should rise to roughly $4 billion (USD) by the year 2026, with North America continuing to account for over 50% of the market share.[4] One of the companies leading the expansion of the market is FARO Technologies, which I will hereby refer to as FARO. With their global headquarters in Lake Mary, Florida, and their diverse product line appealing to a multitude of industries, FARO is positioned to continue their dominance in the North American and global three dimensional laser scanning markets for the foreseeable future.[5] One of the product lines offered by FARO that continues to grow and evolve, at a speed that draws comparison to Moore's Law, is their Focus series of three dimensional laser scanners. Jay Freeland, former Chief Executive Officer of FARO, stated:

> With the revolutionary Focus3D, FARO provides architects, civil engineers and plant designers with an efficient tool for rapid, seamless and precise documentation of the current status of buildings, plants and construction sites of every kind. The Focus3D offers all the functionalities required by a professional user with a previously unknown level of usability and simplicity.[6,]

To put it simply, he was not wrong. With an intuitive touch screen display, close to one millimeter accuracy, and blazing fast measurement speeds of up to nearly 1,000,000 points per second, the Focus3D certainly made an impact in the growing three dimensional laser scanning industry. In addition to this new high level of accuracy being more easily attainable, the Focus3D did something else: it freed the operator up by utilizing a fully self-contained system that did not include the bulky cords and additional equipment needed by other systems. This new sense of freedom and mobility meant that operators would have fewer constraints in regards to access and time needed on site between scan locations, which was a major draw for many users.

With the capabilities of the Focus3D being suitable for not only the documentation of large environments like a cultural heritage site, but also the quality control and even reverse engineering of parts and products, FARO has been able to draw in clientele from multiple fields of study and areas of expertise. This diverse set of clientele is divided into four (4) primary categories by FARO: Factory Metrology, Construction BIM, Product Design, and Public Safety-Forensics. Each primary clientele category consists of multiple sub-categories, or applications, with products and solutions offered based on need. As an example, the category of Construction BIM is divided up into five (5) sub-categories/applications: Architecture, Construction, Engineering, Civil/Survey, and Heritage.[7] This study will focus on the latter, Heritage.

The Global Heritage Fund (GHF) estimates that in the United States less than one quarter of one percent of the philanthropic funding each year is allocated for cultural heritage preservation, and globally total support from all international heritage conservation groups was less than $100 million in 2009, despite the continued revenue produced by tourism at heritage sites.[8] Although more recent data has been difficult to locate and access, it is unlikely that this situation has improved in recent years. Because of this lack of funding for conservation purposes, in combination with the competitive nature of grants and other funding sources, many owners and managers of heritage sites might not have a large budget to work with. Due to this, when exploring documentation options for a site or structure, they most likely have limited abilities to purchase the newest, or latest, documentation equipment such as a three dimensional laser scanner themselves, or contract out the documentation work to a professional or academic group. In many cases there are multiple projects or possible uses for the documentation equipment in question on a site, which could indicate that purchasing the equipment might be the better long term solution, in contrast to contracting out the work on multiple occasions.

But choosing the three dimensional laser scanner, or hardware, that you want to use is just the first step. After choosing which hardware will best suit your needs, the next step is choosing a processing software to utilize for registering and processing the data collected. Many of the producers of three dimensional scanning hardware also have a proprietary software available to customers that can be used in processing the collected data. There are however an increasing number of 3rd party open source software programs that are also available, in addition to some options where the source code is available. However, because processing and registering point clouds often requires the crunching of large data sets, users are likely to choose the software available from the hardware provider that was selected, under the assumption that it is the best tool for the job. Some 3rd party software providers, such as Vercator, are working to overcome those assumptions and are claiming faster and more accurate automatic processing rates,[9] but those options are not yet available on the market at the time of this study.

1.2. Statement of the Problem

In the past, three dimensional laser scanning deliverables and outputs were limited by the capabilities of the processing software available, in combination with the limitations of computing power at the time. However, in recent years the software used to process three dimensional laser scans has advanced significantly, providing better algorithms and more options when completing processing functions. Additionally, when choosing a processing software there are more options than we have ever seen before with an ever increasing number of 3rd party open source software programs that are able to process and register point cloud data. This, in combination with computing power becoming less of a limitation due to the advancements associated with Moore’s Law, has opened up endless possibilities of use for the data that is collected and processed. These new possibilities have been a major factor in the growth of the three dimensional laser scanning industry over recent years,[10] arguably a more important factor than the physical changes seen in the actual three dimensional laser scanner hardware over the same time frame. Although there have been advancements in the hardware, such as increased range, smaller laser diameters, and more portable systems, the overall design and technology used has not greatly changed in recent years.

Therefore, should someone decide to utilize a three dimensional laser scanner to document a heritage site or structure they must ask themselves, “Do I need the newest or latest model that is available, or will an older model satisfy my needs if the data is processed in a current version of the software that is available?” For this study, the manufacturer FARO was selected over Z+F, TI Asahi, Trimble, Surphaser, & Artec based on global market share,[11] and the models being tested are the Focus S 350, which is the latest release in the Focus line, and its predecessors the Focus3D and Focus3D x330 HDR.

1.3. Research Hypothesis

In this study it is hypothesized that we are no longer limited by the combination of software and hardware used in processing the collected data, but are instead facing limitations based on the hardware available to collect the data. Confirming this hypothesis will depend on multiple factors such as the intended deliverable (line drawings vs. Orthographic photos vs. 3D models/meshes vs. raw point cloud data), the level of accuracy desired (HABS level documentation vs. construction drawing tolerances vs. interpretive model for display), and the experience and skill level of the operator (in regards to gathering and collecting the data, registering and processing the data, as well as interpreting the data). However, for common deliverables such as orthographic photos and 3D models/meshes the use of older hardware systems should be capable of providing the intended deliverable with no significant observable differences when compared with data collected by newer laser scanner systems, as long as the data collected is processed using current software programs that are available. Although these deliverables will not be produced for the purpose of this study, the analysis conducted on the data sets collected will indicate if there are any significant differences in the resulting point clouds based on the hardware used to collect the data.

1.4. Objectives of Study

The objective of this study is to determine if there are any significant differences in the output of various three dimensional laser scanning systems that have been released in recent years. More specifically, this study will conduct a comparative analysis using three different iterations of the same product line of three dimensional laser scanners from a single manufacturer, released over a period of 6 years, to document three structures using identical data gathering settings and using the same processing software, to compare the resulting point clouds in an effort to determine if there are any significant observable differences in the data collected by each of the three systems.

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2. LITERATURE REVIEW

The literature review completed for this thesis explored a diverse set of sources and documents and is focused on two specific areas: the growing need for the digital documentation of heritage sites and structures, and the advancements in 3D laser scanning systems and the prevalence of those systems in today's heritage recording efforts.

2.1. The Need for Digital Documentation

In April 2019, tragedy struck the historic Notre-Dame Cathedral in the form of a fire that destroyed the cathedral's spire and lead-covered wooden roof. The nearly 860 year old structure has been widely viewed as one of the most stunning examples of French Gothic architecture in existence today, and was designated a World Heritage Site in 1991.[1] Due to this popularity and appreciation of the structure's beauty, along with its storied past, it is no surprise that the events surrounding its fire damage were extensively covered by media sources around the world. Although these events were tragic in nature, there may be a silver lining to the story as they put the need for detailed digital documentation on the world stage.

Despite the site's inclusion in literature throughout its lifespan, including numerous textural references and thousands, if not millions, of photographs, there is a need for more detail in the form of measurable data to properly restore the site. Thankfully, in 2015 that data was collected by a historian in the form of laser scanning point clouds.[2] These documentation efforts, combined with the historical records available, will allow the process of the cathedral's restoration to be completed with a level of detail that most sites struck by catastrophe are never afforded.

Fortunately, Notre-Dame is not alone in regards to the use of detailed documentation being utilized in recovery from a disaster, whether it be caused by natural phenomenon or man-made. Other notable examples here in the United States include the White House, the Washington Monument, Beauvoir, Saint Michael's Cathedral, and the Honey Run Bridge.[3] Similar to Notre-Dame, the damage sustained at the White House, Saint Michael's Cathedral, and the Honey Run Bridge were all caused by fire, whereas the damage to the Washington Monument was the result of an earthquake, and the damage to Beauvoir was caused by Hurricane Katrina.[4] Despite the diverse causes of destruction and damage to these sites, highly detailed documentation, some cases in the form of digital files such as point clouds, were the key to their repairs.[5] It is through these detailed documentation efforts that sites such as these can respond quickly and effectively following disaster situations,[6] and because of this they are able to withstand the test of time and be experienced by future generations.

Beyond the need to conserve sites for future generations, there is also a need for surveying via detailed digital documentation of heritage sites, both known and unknown, to better understand them for assessment and interpretation purposes. When assessing a heritage site the data collected through devices such as three dimensional laser scanners can assist those involved by providing them with the freedom to view and conduct analytical investigations based on viewpoints and perspectives that may not have been considered or available previously.[7] The data can also be used in the monitoring of sites, and to assess condition changes over an extended period of time should documentation be repeatedly collected at specified increments of time.[8] Alternatively, the data can be collected and utilized in the interpretation, or representation, of a heritage site for those interested through the use of computer-generated images (CGI) and other visual elements that can be provided either on site or in a digital format available through the web.[9]

2.2. The Increased Use of 3D Laser Scanning Systems

Although three dimensional documentation is quickly becoming common practice today that has not always been the case. It wasn't until the 1990's when forms of computer-aided design (CAD) had become commonly used in universities and professional offices, and terrestrial laser scanning systems had become available for use outside of the atmospheric sciences and defense programs, that we began to see a shift in the focus from 2D to 3D in regards to heritage documentation efforts.[10] Although this shift is often thought to be the result of the integration of CAD into the workflow, it is also important to note the advancements in both the hardware and software used specifically in laser scanning systems.

Advancements in the hardware systems used have been similar to many other forms of technology in respect to both the reduction in unit size, and speed in which the task can be performed.[11] Beyond the overall changes observed in the industry these advancements have also led to a plethora of options when selecting a type of three dimensional laser scanner to utilize in documenting heritage sites. While this study utilizes three phase shift terrestrial systems, there are many other options that could be explored in future research. Alternative systems can vary in both the basis of the technology used, for example time-of-flight systems, and in the method of data gathering, such as mobile backpack units. Although this abundance of options may make the selection process more difficult, it is also beneficial in that it provides the user an opportunity to select the solution that best fits the needs of the project or site.

However advancements in the software used to process and utilize the data have been arguably just as important, if not more important in recent years.[12] What might have taken a desktop customized for registering and processing the data multiple days to complete a decade ago can now be completed by less expensive mobile counterparts, like laptops and tablets, in just hours today. Although this shift from 2D to 3D has been primarily been spurred by technological innovation in both the hardware and software used over recent decades, it should be noted that it has also required a cultural change in both the way we think about documentation and gathering data, as well as the expectations of the final products or deliverables in heritage documentation,[13] which will be discussed later in this literature review.

Despite the aforementioned shift, there is still a need for a variety of documentation methods and techniques in the field of heritage documentation, partially due to the variance in budget constraints from site to site, and project to project.[14] One researcher identifies these varied methods of documentation as simple and complex collection systems. They refer to simple tools as those that existed prior to the digital age and gather data through forms of measurement that are direct. These would be tools such as traditional tape measures, profile combs or contour gauges, and other tools that require little training to operate and limited funds to acquire. In contrast, complex tools are referred to as those that utilize digital technologies and have impacted the way in which documentation is conducted through indirect means. Examples of these tools include technologies such as total station theodolites and three dimensional laser scanning systems where data is collected through the devices storage system, or memory, and later converted and manipulated through the use of computers and software programs.[15] Both collection systems have their respective benefits and limitations therefore it is important to assess the options on a case by case basis for each project or site. Those undertaking the task of detailed documentation on a site should strive to maintain a balance and not focus on one tool or one method exclusively.[16]

One area where the two collections systems vary greatly is in regards to cost. Simple collection systems tend to cost far less than their complex counterparts, and this can be an issue for many heritage sites due to limited funding.[17] Given the severity of these funding issues, as the GHF estimates that only one-quarter of one percent of philanthropic funding in the United States is designed for the preservation of cultural heritage,[18] funding can be a major factor in choosing which method of data collection will be used on a particular site. Fortunately in recent years the cost of the hardware used in these complex data collection systems has decreased making them more available than ever before.[19] The results of this study may help to further overcome the issue of cost in some locations should the results indicate that comparable results, in regards to deliverables and project outputs, can be achieved using older and presumably cheaper models of these complex data collection systems, such as three dimensional laser scanners.

In addition to the overall cost of these systems lowering over time, there have also been more options, or alternatives, introduced on the market that allow those conducting heritage documentation to select a system that best fits their needs at various price points. One such example of this is the introduction of the BLK 360 by Leica which is significantly cheaper than many of the other systems, yet provides a similar result, albeit at a presumed lower quality in regards to the density of the data collected. Another example is the introduction and advancement of mobile, or portable systems, such as those contained in a backpack. These systems provide even greater flexibility to the operator given they are able to collect data while moving, as opposed to the stationary systems that we typically associate with three dimensional laser scanning.

However budgetary constraints are not the only factor when considering which system to utilize. It is also important to consider the intended final deliverable, or use, of the data collected. Through a processes known as vectorization a user can create various deliverables or documents including plans, sections, and elevations, all of which are often an important part of documenting cultural heritage sites.[20] Additionally, the user has the option to create these deliverables based on multiple versions of the data, ranging from the original registered point cloud that was created to orthographic images and meshes created from that point cloud.[21] It is important to note however that the outputs of the vectorization process can be influenced by the user.

Furthermore, should the desired output of the data collected be those created through the vectorization process of a registered point cloud, it is important for those involved in the process to determine if laser scanning and the creation of a registered point cloud is necessary. Despite being the one of the latest technological advancements in heritage conservation and documentation, terrestrial three dimensional laser scanning systems and the creation of a registered point cloud with a high density of collected measurable points is not always the best fit. In some cases the use of the alternatives, such as the previously mentioned BLK 360 or portable backpack systems, may be a better fit for the need being addressed. And in other cases simple collection methods such as hand measuring, or more basic complex collection methods like the use of total station theodolites, may be better suited to fulfill the needs of the documenter. In these cases registered point clouds created through the process of laser scanning may be considered overkill due to the relatively large file sizes and complexity of the data sets created.[22] Additionally, sharing the data sets can be difficult in many situations due to the size of the data sets in combination with the need for specialized software in viewing the created point clouds. Therefore it is important for the owner or operator of a heritage site and the individual completing the documentation process to design a schedule of fieldwork, and select an appropriate system to be used in that fieldwork, that meets the specific needs of the project and the intended final deliverable in an effort to avoid overly complicating the process and using a system that is not appropriate for the situation.[23]

However, I believe the evidence suggest that should the use of a terrestrial three dimensional laser scanner and the creation of a registered point cloud of high density be deemed reasonable, and within the constraints of a heritage site, that efforts should be made to complete this form of documentation and obtain as much data on the site in question as is possible. That way in case of a disaster, either by natural phenomenon or man-made, there is adequate highly accurate empirical data to restore, rehabilitate, or represent the site digitally, for future generations to experience.

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3. METHODOLOGY

3.1. Overview

This study is a comparative analysis of multiple laser scanning point cloud data sets, collected on three early 20th century buildings located on the Texas A&M University main campus with three different iterations of a single product line of three dimensional laser scanning models released over the course of six years, in an effort to determine if there are significant differences in the resulting data. Each data set was collected, processed, and analyzed by the researcher, although some data was collected with the assistance of a research team of students, over the course of four years. All data was registered and processed using a recent version of the manufactures software program to limit variables due to the elapsed time. Analysis of the data includes both visual and empirical elements in an effort to provide a result that is both technical and functional. This analysis will be discussed in section 4 of this study.

3.2. Selection of Buildings/Sites

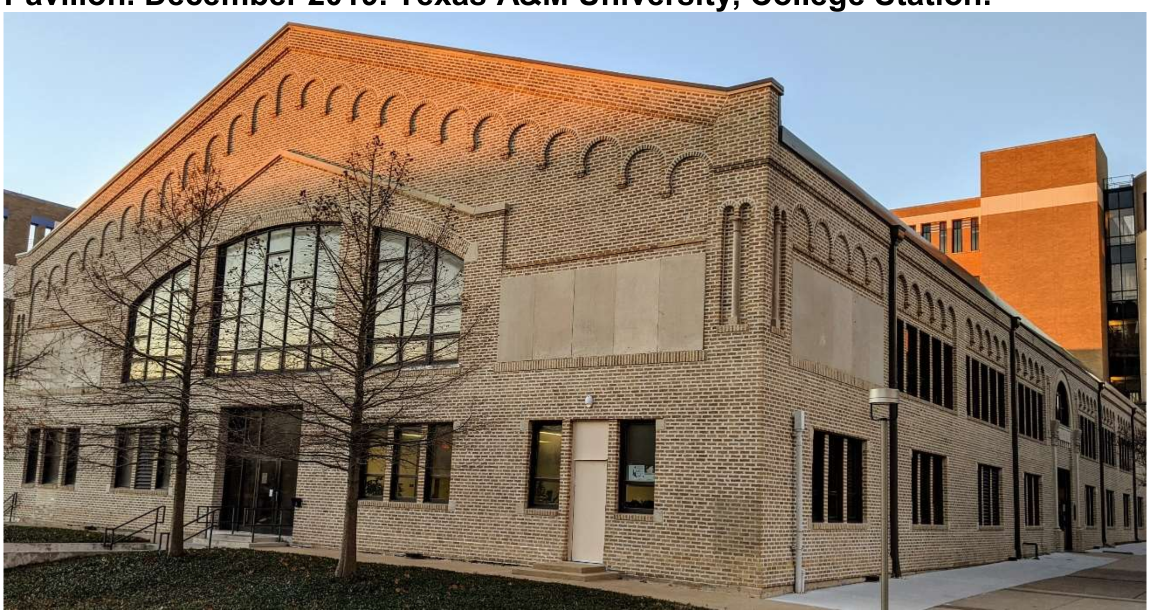
For this study three early 20th century building exteriors on the main campus of Texas A&M University were documented using three dimensional laser scanning systems. The three building exteriors were initially scanned with a FARO Focus3D (120m model) during the summer of 2015 by a team of students under the guidance of Professor of Architecture, Robert Warden. All three building exteriors are easily accessible and had no major changes or renovations since being originally scanned in 2015, and later scanned in 2019. The three buildings are the Cushing Memorial Library, the Animal Husbandry Pavilion, and the Y.M.C.A. building.

Cushing Memorial Library, shown below in Figure 3.1, was built in 1930 and designed by Frederich Giesecke and Samuel C. P. Vosper, with the help of Philip Norton. Named after Col. Edward Benjamin Cushing, class of 1880, it was the first building on campus to be built as a Library. It is neoclassical in style with typical Vosper ornamentation details on the façade in the form of ram head and cow skull pilasters. In 1968 the Sterling C. Evans Library was adjoined to the northeast side of the building, but the remaining three sides of the original Cushing Memorial Library still stand today. Restoration and renovations efforts were undertaken in 1998 and the building remains in use to this day.[1]

Figure 3.1 – Billingsley, Andrew. West corner of Cushing Memorial Library. December 2019. Texas A&M University, College Station.

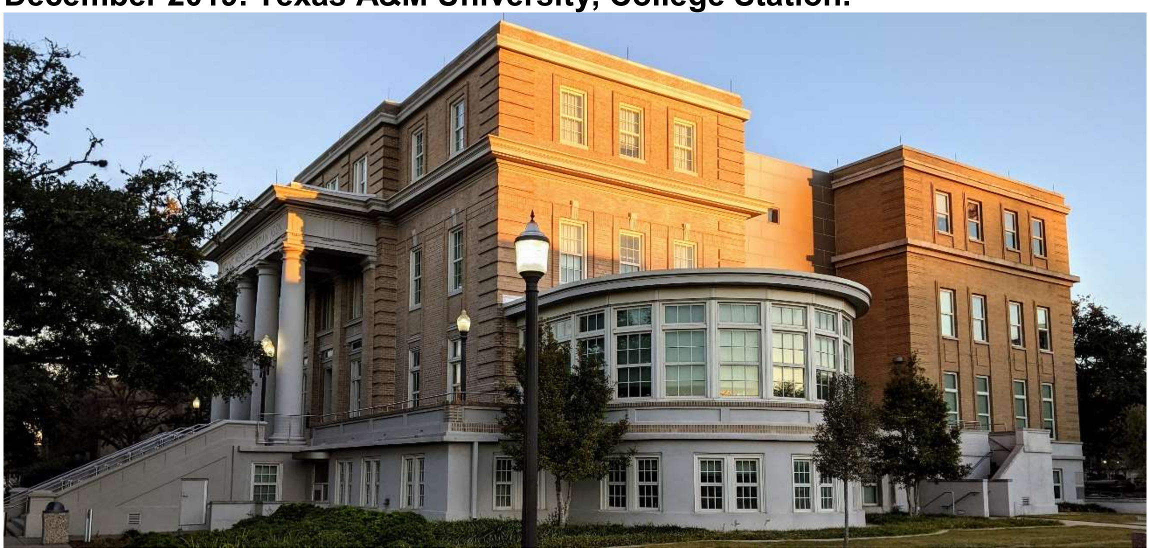
The Animal Husbandry Pavilion was designed by Rolland Adelsperger and built in 1917. Throughout its lifespan the building has endured multiple uses including use by the U.S. military during WWI as an aircraft hangar. Its original Beaux-Arts style Romanesque-inspired features, shown below in Figure 3.2, can still be seen on the façade today, despite its renovation in 1988 to provide office space for registration, student financial aid, and student activities, among others.[2]

Figure 3.2 – Billingsley, Andrew. North corner of the Animal Husbandry Pavilion. December 2019. Texas A&M University, College Station.



The Y.M.C.A. building was another design of Frederich Giesecke, but this time with the assistance of Sampson J. Fountain. Built in 1914 and located on Military Walk, it was the first building to be constructed on campus with a social focus (which included a chapel, a bowling alley and a pool), and was a hub of campus life for many years. Notable events to take place there include the first Midnight Yell which was held on the front steps in the 1930's. Classical Revival style with a main portico supported by four (4) two story tall Doric columns at the top of the front stairs, and two half-circle rotundas on the northwest and southwest corners, shown below in Figure 3.3, it is a hard building to miss when passing by. Renovations were undertaken in 2011 and the building remains a staple of campus to this day.[3]

Figure 3.3 – Billingsley, Andrew. South corner of the Y.M.C.A. Building. December 2019. Texas A&M University, College Station.



3.3. Selection of Hardware

This study utilized three different iterations of the same three dimensional laser scanning product line from a single manufacturer, FARO Technologies, released over a period of 6 years. Those three models are the Focus3D (120m model), the Focus3D x330 HDR, and the Focus S 350. These three laser scanning systems were selected for two reasons. First, FARO is one of the leading three dimensional laser scanning system manufactures in the United States of America, and globally.[4] Second, the Center for Heritage Conservation at Texas A&M University has access to all three models and has used them on multiple documentation projects.

When comparing the specifications of each model, you can see that many similarities and differences exist between the original Focus3D (120m model released in 2010), and it successors the Focus3D x330 HDR (released in 2013) and later the Focus S 350 (released in 2016).[5] Noticeable similarities include:

1. Size and weight
    - The Focus3D and Focus3D x330 HDR are identical in size, and nearly identical in weight.
        i. Both are 240 mm x 200 mm x 100 mm;
        ii. The Focus3D is 0.2kg lighter than the Focus3D x330 HDR, 5.0kg and 5.2kg respectively.
    - The Focus S 350 is slightly smaller in size, and lighter in weight, than both of its predecessors coming in at 230 mm x 183 mm x 103 mm and 4.2kg respectively.
2. Measurement speed
    - All three boast a measuring speeds (points/second) of 122,00/244,000/488,000/976,000

3. Defection unit (field of view and maximum vertical scan speed)
    - The original Focus3D has a slightly larger field of view vertically in comparison to its successors, 305° vs 300°, but all three models cover 360° horizontally;
    - All three models have a maximum vertical scan speed of 97Hz, or 5,820rpm.
4. Battery life
    - All three models have effectively the same battery life of roughly 4.5 hours;
    - The Focus3D specification sheet claims “up to 5 hours” of use, compared to the more definitive number of 4.5 hours stated by its successors.
5. Operating conditions
    - All three models require an operating ambient temperature range of 5°C to 40°C, and a non-condensing level of humidity.
6. Data storage
    - All three models can utilize SD/SDHC/SDXC memory cards, and all three include a 32GB card when purchased.

Although there are many similarities, there are also noticeable differences to take into consideration when comparing the three models. Notable differences include:

1. An increase in maximum range (with 90% reflectivity)

- 0.6 m – 120 m with the Focus3D;
- 0.6 m – 330 m with the Focus3D x330 HDR;
- 0.6 m – 350 m with the Focus S 350.

2. A decrease in ranging noise at both 10 m and 25 m (with 90% reflectivity)
    - 0.6 mm at 10 m, and 0.95 mm at 25 m, with the Focus3D;
    - 0.3 mm at 10 m, and 0.3 mm at 25 m, with the Focus3D x330 HDR;
    - 0.3 mm at 10m, and 0.3mm at 25m, with the Focus S 350.
3. An upgraded color unit
    - Up to 70 megapixels with the Focus3D;
    - Up to 170 megapixels, and the option to use HDR exposure bracketing (3x/5x), with the Focus3D x330 HDR;
    - Up to 165 megapixels, and the option to use HDR exposure bracketing (2x/3x/5x), with the Focus S 350.
4. A decrease in ranging error
    - ± 2 mm with the Focus3D;
    - ± 2 mm with the Focus3D x330 HDR;
    - ± 1 mm with the Focus S 350.
5. A decrease in laser (optical transmitter) beam diameter at exit, due to a change in wavelength.
    - 3.00 mm using a 905 nm wavelength with the Focus3D;

- 2.25 mm using a 1550 nm wavelength with the Focus3D x330 HDR;
- 2.12 mm using a 1550 nm wavelength with the Focus S 350.

6. Laser Class
   - A Class 3R laser, which can be hazardous to your eyes if exposed continuously at close range, used in the Focus3D;
     i. Under common scan settings, Resolution set at 1/4 and Quality set at 3x were used for this study, the hazardous viewing distance (assuming continuous exposure) is 7.5 m vertically and 2.80 m horizontally, from the optical transmitter.
     ii. Class 1 lasers, which are eye safe even under extended viewing circumstances (as long as you are not using a magnifying optical instrument, like binoculars), are used in the Focus3D x330 HDR and Focus S 350.

These similarities and differences are also provided on the next page in Table 3.1, which was compiled based on the information provided by FARO in each of the laser scanners provided Tech Sheets.[6, 7, 8]

Table 3.1 – FARO Focus series laser scanner model comparison, adapted from the Tech Sheets published by FARO Technologies.

Model	Focus 3D (120m)	Focus 3D x330 HDR	Focus s350
Dimensions	240mm x 200mm x 100mm	240mm x 200mm x 100mm	230mm x 183mm x 103mm
Weight	5.0kg	5.2kg	4.2kg
Battery Life	Up to 5 hours	Up to 4.5 hours	Up to 4.5 hours
Operating Conditions	5°C to 40°C (and a non condensing level of humidity)	5°C to 40°C (and a non condensing level of humidity)	5°C to 40°C (and a non condensing level of humidity)
Data Storage	SD/SDHC/SDXC	SD/SDHC/SDXC	SD/SDHC/SDXC
Measurement Speed	122,000/244,000/488,000/976,000 (points/second)	122,000/244,000/488,000/976,000 (points/second)	122,000/244,000/488,000/976,000 (points/second)
Deflection Unit	-	-	-
- Field of View	305° Vertically, 360° Horizontally	300° Vertically, 360° Horizontally	300° Vertically, 360° Horizontally
- Vertical Scan Speed (MAX)	97 Hz (5,820 rpm)	97 Hz (5,820 rpm)	97 Hz (5,820 rpm)
Range	-	-	-
- Minimum (with 90% reflectivity)	0.6m	0.6m	0.6m
- Maximum (with 90% reflectivity)	120m	330m	350m
Ranging Noise	-	-	-
- 10m (with 90% reflectivity)	0.6mm	0.3mm	0.3mm
- 25m (with 90% reflectivity)	0.95mm	0.3mm	0.3mm
Ranging Error	± 2mm	± 2mm	± 1mm
Color Unit	-	-	-
- Megapixels	Up to 70	Up to 170	Up to 165
- HDR Enabled	NO	YES	YES
- HDR Exposure Bracketing Options	N/A	3x/5x	2x/3x/5x
Optical Transmitter (laser beam)	-	-	-
- Classification	Class 3R	Class 1	Class1
- Eye Safety Distance (w/settings on 1/4 & 3x)	7.5m Vertically, 2.8m Horizontally	Any	Any
- Diameter at exit	3.00mm (905nm wavelength)	2.25mm (1550nm wavelength)	2.12mm (1550nm wavelength)

3.4. Selection of Software

The software program utilized in this study, SCENE 2018.0.0.648, was also produced by FARO Technologies. From this point forward I will refer to it as SCENE. The software program was used to register and process the data sets that were gathered by each of the three dimensional laser scanning systems. SCENE was selected for the processing of the raw data because it is the proprietary software available from FARO and was designed to function with the data gathered by their laser scanner systems. Additional details regarding this process can be found in section 3.6 of this study.

3.5. Data Gathering Process

The data used in this study was collected in the following manner. Once each building was selected the researcher visually assessed each site and determined the minimum number of scan locations needed to provide adequate coverage of each building façade and footprint. Given that this study was not focused on each individual feature of the buildings selected, the researcher determined it was not pertinent to ensure that every surface was completely recorded, however it was important to ensure that all unobstructed walls, windows, and doors were included. This assessment resulted in the researcher choosing the following number of scan positions for each building:

- Cushing Memorial Library – 9 scan positions
- Animal Husbandry Pavilion – 16 scan positions
- YMCA – 14 scan positions

The specific scan locations were selected to insure that there was significant overlap between locations, to increase the density of points and detail in the combined point clouds, and so that major building features were included.

As Cushing Memorial Library was the most unobstructed building and most open site of the three it required the least number of scan locations to provide the desired coverage. However, as the building is physically attached on the northeast side to the Sterling C. Evans Library main building, built in 1968, it was only possible to scan Cushing Memorial Library on the three remaining sides.[5] These nine scan positions can be seen in Figure 3.4 on the next page.

Figure 3.4 – FARO Scene Overview Map showing the scan locations used on Cushing Memorial Library, the FARO Focus 3D data set is shown.

Similarly, the YMCA building was only scanned on three of the four main facades, but for different reasons. Due to the obstruction of low hanging tree branches in close proximity to the façade on the northeast side of building it was decided that only the three less obstructed sides would be scanned for this study. These scan locations can be seen in Figure 3.5 shown on the following page. Although it was only scanned on three sides as well, more scan locations were necessary due to the layout and design of the building, in particular the two half-circle rotundas on the northwest and southwest corners, and the large portico on the west side of the building.

Figure 3.5 – FARO Scene Overview Map showing the scan locations used on Y.M.C.A Building, the FARO Focus 3D data set is shown.

In contrast, the Animal Husbandry Pavilion was scanned on all four sides as there were fewer obstructions. These scan locations can be seen in Figure 3.6 on the next page. It required the largest number of scan positions due to this additional side, in combination with the need for the majority of scans to be in close proximity of the building due to adjacent structures on the south and west sides, and landscaping on the north side. The east side of the building also contained landscaping elements, but due to their sparsity scan positions were able to be located farther away from the building.

Figure 3.6 – FARO Scene Overview Map showing the scan locations used on Animal Husbandry Pavilion, the FARO Focus 3D data set is shown.

It should be noted that all three buildings had landscaped elements present in the scans and data was collected to the best of the researcher's ability from unobstructed locations. However, due to the time duration between scanning events some of the landscaping elements, such as trees and bushes, do obstruct more of the building facades in the later scans. This is one reason why the researcher decided to trim the combined point cloud data sets at the base of each buildings facades, which is discussed in more detail in Section 3.6.

Once the scan locations were selected the first set of data was collected by the researcher and a team of students during the summer of 2015. The students were enrolled in ARCH 485-102, a 5-week, 3-credit, Directed Study course on the Recording of Historic Buildings under the guidance of Professor Robert Warden. Although this documentation took place over the course of several weeks due to other tasks that were being undertaken as a part of the course, it was decided that for the purpose of this study the scanning of each individual building should be completed in a single day to limit possible variables such as weather changes and temporary obstructions.

For each scan location the research team would first set up the supporting tripod for the laser scanner and level it to the best of their abilities using the built in bubble level. After attaching the laser scanner to the tripod the team then adjusted the necessary parameters and sensors that would be used, and created any necessary project file names within the scanning unit being used at a given time. For the purpose of this study the researcher ensured that the parameters and sensors used stayed consistent between each scanner used and each set of data collected. The two main parameters that the researcher needed to ensure stayed consistent between all scans conducted were the Resolution and Quality settings of the each scanning system.

The Resolution setting relates to the number of scan points collected on each rotation of the mirror projecting the laser.[9] For this study a Resolution of ¼ was selected, meaning that the scanner only recorded one out of every four data points measured for each degree of rotation made by the scanning unit. This value was chosen for four reasons. First, as the study was not focused on the specific details of each building, but instead on the general features of the façade and footprint, it was not necessary to collect every data point measured by the scanning unit. Second, a Resolution of ¼ provides a large enough data set under the scanning conditions, more specifically based on the distance of the scanner in relation to the building being scanned, to adequately show the general features each building. Although a larger Resolution, such as ½ or 1, would result in a higher density data set, it was not deemed necessary for this study. It should be noted that in some situations the point cloud data when processed was denser due to some scan locations being located closer to a given façade. One example of this is the portico of the Y.M.C.A. building. The third reason was simply due to time and efficiency, as the larger the Resolution value the longer each individual scan takes due to the mechanical functionality of the laser scanning systems. Lastly, the fourth reason was due to the resulting file sizes of larger value Resolutions, the larger the Resolution value and the denser the data the larger the file size. And because denser data in turn required more time and processing power, in regards to the computer hardware used, it was decided that the value of ¼ was appropriate for the study.

The Quality setting relates to the amount of noise in the data collected, with a higher value resulting in less noise within the data set.[10] The value of 3x that was chosen indicates that the scanner filtered the data collected three times during the collection process, in contrast to a quality setting of 1x that would have only complete this process once. Similar to the choice of ¼ for the Resolution setting, the Quality setting of 3x was selected due to efficiency, and data set file sizes. The combination of these two settings has proven to be effective in past projects completed by the Center for Heritage Conservation

(CHC) at Texas A&M University, who possess and use the scanners on a regular basis, and these settings will most likely be used on future projects completed by the CHC given the balanced results that are produced.

Once all settings were adjusted at a given scan location the team started an individual scan and ensured that they were out of the area of focus for the study. Each scan location took roughly 8 minutes to record all of the necessary data and at that point the team would move the scanner and tripod to the next location and repeat the process until all scan locations had been recorded for a given building. The resulting data was then transferred from the memory card used by the scanner hardware to a computer for storage and processing.

Using the data sets from the initial scanning project in the summer of 2015 as a guide subsequent data with the newer FARO Focus models, the Focus3D x330 HDR and the Focus S 350, were collected in the spring of 2019. The researcher ensured that all scan locations and scanner settings, including the Resolution and Quality settings, were as consistent as possible between all data sets. As there were no permanent markers or indicators used when selecting the scan locations during the initial data collection process the researcher utilized SCENE overview maps from each project file, which were shown earlier in this section, in combination screenshots collected to determine the subsequent laser scanner positions with the remaining two systems.

3.6. Point Cloud Registration and Processing

Each data set was first processed in SCENE 2018.0.0.648. The initial processing of the data by SCENE, after importing the raw scan data that was collected, is what I will refer to as pre-processing. The settings used for pre-processing were those set by default from the manufacture and were as follows:

- General:
    - Create Scan Point Clouds – SELECTED
    - Skip Fully Processed Scans – SELECTED
- Colorization
    - No Colorization – NOT SELECTED
    - Colorize Scans – SELECTED
    - Laser Illuminated HDR – NOT SELECTED
- Filters
    - Dark Scan Point Filter – SELECTED
        - Settings
            - Reference Threshold – 200
    - Distance Filter – NOT SELECTED
    - Stray Point Filter – SELECTED
        - Settings
            - Grid Size – 3 px
            - Distance Threshold – 0.02 m
            - Allocation Threshold – 50%

    - Edge Artifact Filter – NOT SELECTED
- Find Targets
    - Find Checkerboards – NOT SELECTED
    - Find Markers – NOT SELECTED
    - Find Planes – NOT SELECTED
    - Find Spheres – NOT SELECTED
- Automatic Registration
    - Perform Automatic Registration – NOT SELECTED

After importing and pre-processing the raw scan data in SCENE, registration was completed using the Top View and Cloud to Cloud method. The Settings used for registration were based on the software defaults and were as follows:

- General:
    - Use Inclinometer - SELECTED
    - Use Compass – SELECTED
    - Expert Settings:
        - Move cluster to the center of its scans – SELECTED
- Top View
    - Subsampling – 0.035m
    - Reliability – 0.35m
    - Calculate Target Based Statistics – NOT SELECTED
- Cloud to Cloud
    - Subsampling – 0.050m

    - Calculate Target Based Statistics – NOT SELECTED
    - Expert Settings:
        - Maximum Number of Iterations – 30 Iterations
        - Maximum Search Distance – 10.00m

The results of the registration process for each data set will be discussed in section 4.1.2 of this study. After registration project point clouds were created for each data set using the following settings based on the software defaults:

- Filter Settings
    - Eliminate Duplicate Points – SELECTED
        - Slider set in middle of scale from Low to High
    - Close Surfaces – NOT SELECTED
    - Homogenize Point Density – NOT SELECTED
    - Apply Color Balancing – SELECTED
    - Distance Filter – NOT SELECTED

Figure 3.7, located on the next page, shows an example of a project point cloud created of the Cushing Memorial Library before being trimmed. The point cloud data was then trimmed by the researcher at the base of each building's exterior walls to remove features not directly associated with the building. The surrounding data, such as landscaping and people, was removed to avoid possible outliers in the comparison process in. Figure 3.8, which can also be seen on the next page, shows an example of a trimmed project point cloud of Cushing Memorial Library where features not related directly to the building have been removed. Each point cloud data set was then exported as an .e57 file, a vendor neutral point cloud format, to compare and analyze the data sets.

Figure 3.7 – Isometric view of Cushing Memorial Library untrimmed point cloud, looking north, created using the FARO Focus3D x330 HDR.

Figure 3.8 – Isometric view of Cushing Memorial Library trimmed point cloud looking north, created using the FARO3D Focus x330 HDR.

3.7. Comparing the Point Clouds

An initial visual comparison was completed first. During this process the researcher looked for and assessed any obvious visual differences in the point clouds created by each laser scanning system. Possible differences include things like missing or incomplete data which were often caused by visual obstructions present during the various data collection periods, and major renovations or changes that occurred during the duration of the research. The results of this stage of analysis will be discussed in section 4.1.1 of this study. Following this initial visual comparison the researcher then compared the registration reports for each individual data set. These reports helped the researcher confirm that each data set was processed and registered properly and did not show any major discrepancies that needed to be addressed, which would have been apparent in the values provided in the reports. This analysis is provided in section 4.1.2 of this study.

Following the visual comparison, and the review of each data set's registration report, the exported .e57 files were imported into a new project file in SCENE to compare the outputs from each laser scanner against one another. Once imported the scans were pre-processed using the settings discussed in section 3.6 of this study. Once pre-processed the data sets were registered together utilizing the Cloud to Cloud option in SCENE with the following settings:

- General:
    - Use Inclinometer - SELECTED

    - Use Compass – SELECTED
    - Expert Settings:
        - Move cluster to the center of its scans – SELECTED
- Cloud to Cloud
    - Subsampling – 0.050m
    - Calculate Target Based Statistics – NOT SELECTED
    - Expert Settings:
        - Maximum Number of Iterations – 30 Iterations
        - Maximum Search Distance – 10.00m

The Cloud to Cloud registration setting was used in order to provide data, via registration reports, on the alignment of the three (3) data sets for each building in the study. These registration reports, and analysis of the results, are discussed in section 4.2 of this study.

In addition to the visual analysis and comparison of the registrations reports, the researcher conducted measurements on each of the buildings main facades, in each of the data sets collected. Horizontal, vertical, and diagonal measurements, of various scales, were collected. In total 99 measurements, 33 from each laser scanning system, were collected and compared against the measurements collected in each of the other two data sets in order to calculate the change in value, or delta, between the laser scanning systems utilized. The measurements collected, and calculated delta values, will be discussed in section 4.3 of this study.

3.8. Endnotes

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10. Faro Technologies, FARO Laser Scanner Focus3D User Manual, November 2018: 50. https://faro.app.box.com/s/8xtj92jnpu011i8crn2qyh1bd6d3s0mo/file/405611057377

4. ANALYSIS OF DATA

4.1. Overview

Analysis of the data began with a visual comparison of each point cloud data set in SCENE. Following the initial visual comparison, the registration reports produced by SCENE were compared in order to look for any distinct similarities or differences in both the individual data sets and as an aligned data set for each building. Lastly, 33 distance measurements, utilizing sharp and distinct features visible in the façades of each building, were taken from each of the collected data sets. These distance measurements were then compared and used to calculate the degree of similarity or difference as an empirical value (delta value) for each set. In addition to the assessment of the delta values, the mean delta from all 99 measurements was also calculated in order to assess the average value of similarity and/or difference among the data sets

4.2. Visual Comparison

During the visual comparison process, the researcher looked for any major inconsistencies in the registered point clouds for each of the buildings before they were trimmed and exported for additional analysis and comparison. For example, potential causes of inconsistencies might include, but are not limited to: missing or incomplete data due to obstructions, major renovations or changes, and anomalies such as vehicles and people who were present during the scanning process with one scanner but not all scanners at a given location.

Special attention was given to areas of incomplete, or missing, data that was caused by obstructions present during the data collection processes. As the obstructions caused areas of the point cloud to be blank or have a lower density of points, they were easily identified when comparing the point clouds.

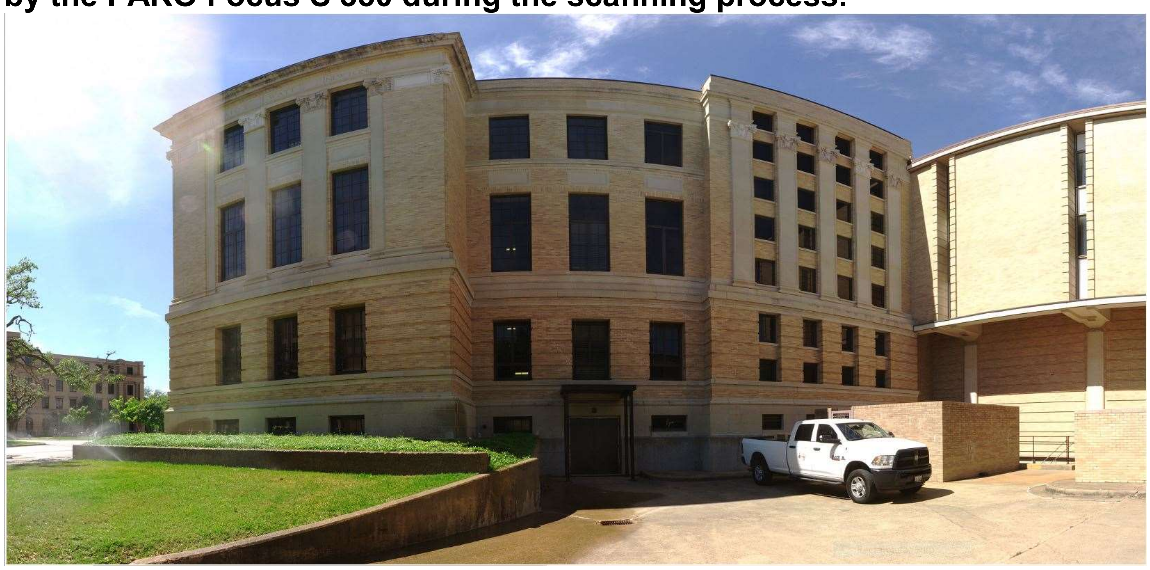
Given that the buildings were located on the main campus of Texas A&M University, it was not possible to fully avoid pedestrian traffic while collecting the data, no matter the timing of the scanning process, without completely closing off the buildings to faculty, staff, and students, which was not deemed necessary for this study. Additionally, due to the time difference between the original scan data being captured, which occurred in 2015, and the subsequent scan data that was captured, which occurred in 2019, there are expected differences in the scan data where landscaping elements are present due to the obstructions caused by those landscaping elements growing over time. Furthermore, as the scan locations for each of the buildings were on the ground level of each building's exterior, with the exceptions of the three scan locations on the main portico of the Y.M.C.A. building, there was data missing on any horizontal features located above the height of the scanner, including roof structures. This was known to the researcher throughout the process and due to logistical issues of limited elevated positions to scan from, it was an accepted limitation.

Cushing Memorial Library

When completing the visual comparison of the point clouds for Cushing Memorial Library, the researcher noted consistent missing, or incomplete, data on the southwest façade due to the handrails on the ADA ramp in all three data sets. Additionally some data is missing on the southern corner of the building due to ground level shrubbery. The point clouds from both the Focus3D x330 HDR and Focus S 350 data sets contained two areas of incomplete data on the northwest façade due to the growth of a tree located on that side of the building, and due to temporary orange construction netting that was present at the time the scans were completed. This can be seen in Figure 4.1 on the next page. In addition to these obstructions, the point cloud from the Focus3D x330 HDR data set was also impacted by a parked travel trailer being used by a construction company working on the building at that time, as shown in Figure 4.1. Similarly, in the point cloud created from the Focus S 350 data set there was a truck parked on the southeast side of the building when the scanning process was completed and due to this there is a small area of impacted data. This can be seen in Figure 4.2 on the following page, which also shows the presence of sprinklers being in use during the data gathering processes at that scan location. As the sprinklers were only active for a short period of time in one scan location, and due to their consistent movement, there was no visible effect from them that was noticed by the researcher. Despite the previously mentioned obstructions, the visual analysis indicates that the point clouds are not significantly different between data sets and there should not be any substantial variations.

Figure 4.1 – Temporary fencing and trailer on the northwest side of Cushing Memorial Library during the data gathering process, captured by the FARO Focus3D x330 HDR during the scanning process.

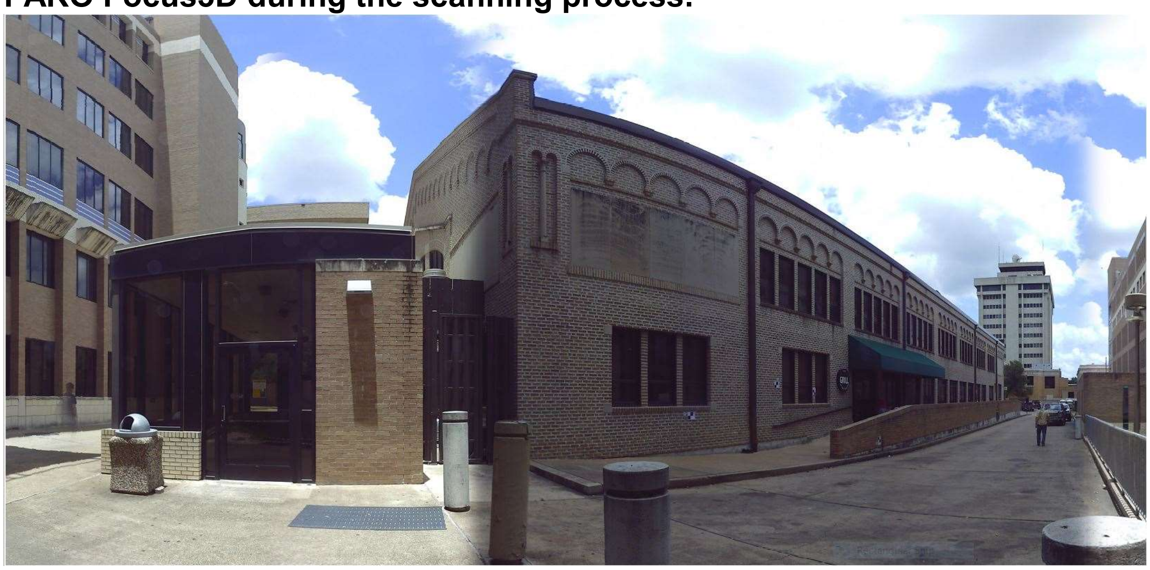
Figure 4.2 – Parked vehicle and active sprinklers on the southeast facade of Cushing Memorial Library during the data gathering process, captured by the FARO Focus S 350 during the scanning process.



Animal Husbandry Pavilion

In regards to the Animal Husbandry Pavilion there are two obstructions causing missing data in all three point cloud data sets. First is a set of four (4) trees that are located on the northeast side of the building, which can be seen in Figure 3.2 on page 23 of this study. The second obstruction was the shading caused by the retaining wall of an elevated walkway on the southeast side of the building. During the data gathering processes the researcher made the decision to place the scan locations outside of this area due to time constraints and in an effort to better capture the façade of the building from a father distance, despite the loss of data it caused. This retaining wall can be seen in Figure 4.3 below.

Figure 4.3 – Retaining wall for elevated walkway blocking the lower portion of the southeast facade of the Animal Husbandry Building, captured by the FARO Focus3D during the scanning process.



Aside from the previously mentioned factors, no additional static obstructions were visible when comparing the point cloud data sets for this building. There were various obstructions that occurred for short periods of time during the scanning process, such as pedestrian traffic and vehicles temporarily moving through the area being scanned. However based on the observations of this researcher those temporary obstructions did not cause any significant changes to the data sets that were collected.

Y.M.C.A. Building

Similarly to the other two buildings in this study the primary cause of incomplete data in the point clouds of the Y.M.C.A. Building is due to landscaping elements, specifically trees and shrubbery. All three (3) point cloud data sets for this building contained incomplete data due to trees planted close to the footprint of the building on the northwest and southeast sides of the building. An example of this can be seen in Figure 4.4 on the following page. Additionally, all three (3) point cloud data sets had obstructed views of the building's southwest façade due to overhanging branches from mature trees located along the northeast side of Houston Street. This can be seen in Figure 3.3 on page 24 of this study. Similarly to the other two buildings there were periods of pedestrian foot traffic during the times when data was collected but as it was not static in nature it does not appear to have caused any significant issues with the data that is visually assessable.

Figure 4.4 – View of the southeast facade of the Y.M.C.A. Building showing trees close to footprint of the building, captured by the FARO Focus S 350 during the scanning process.

4.3. Individual Registration Report Comparison

Although these reports do not directly compare the point clouds that are produced, which will be discussed in section 4.4 and section 4.5 of this study, they do assist in assessing if the data was processed and registered properly as any major discrepancies should be easily apparent in the values provided in the reports. The registration reports for each building and each laser scanner system, are provided in Appendix A of this study, and a summary of the results is provided on the next page in Table 4.1. The values shown for the three primary factors that were assessed, Maximum Point Error, Mean Point Error, and Minimum Overlap, were provided directly by SCENE for each data set shown and represent the overall statistics for all scans that were collected.

Values for individual scan comparisons can be found in the full reports, which are provided in Appendix A of this study.

Table 4.1 – FARO SCENE individual registration report summary.

Summary of Individual Registration Reports - FARO SCENE				
Building	**Category**	**Data**		
Cushing Memorial Library	Laser Scanner Model	Focus 3D (120m)	Focus 3D x330 HDR	Focus s350
	Number of Scans	9 Scans	9 Scans	9 Scans
	Maximum Point Error	5.1 mm	3.9 mm	8.0 mm
	Mean Point Error	2.8 mm	2.8 mm	4.6 mm
	Minimum Overlap	26.0%	27.2%	28.3%
Animal Husbandry Pavilion	Laser Scanner Model	Focus 3D (120m)	Focus 3D x330 HDR	Focus s350
	Number of Scans	16 Scans	16 Scans	16 Scans
	Maximum Point Error	6.6 mm	7.4 mm	8.0 mm
	Mean Point Error	3.0 mm	3.6 mm	4.2 mm
	Minimum Overlap	15.7%	12.5%	18.3%
Y.M.C.A. Building	Laser Scanner Model	Focus 3D (120m)	Focus 3D x330 HDR	Focus s350
	Number of Scans	14 Scans	14 Scans	14 Scans
	Maximum Point Error	6.8 mm	8.3 mm	13.3 mm
	Mean Point Error	3.3 mm	3.8 mm	6.3 mm
	Minimum Overlap	14.0%	13.4%	10.3%

Cushing Memorial Library

When assessing the registration reports for this building a few differences stood out immediately. The most notable differences were in regards to the Maximum Point Error and Mean Point Error of each data set. As shown above in Table 4.1 the Focus S 350 displayed higher numerical values than its two predecessors, despite showing a higher level of overlap between scan locations. Based on the factors mentioned in the visual assessment of the point clouds, section 4.2 of this study, it is the opinion of the researcher that the difference was most likely caused by the obstructions present during the gathering of that data set, more specifically the orange temporary fencing on the northwest side of the building and the parked vehicle on the southeast side of the building.

When assessing the combination of these three factors, the assessment indicates that the best data set collected was the one gathered by the Focus3D x330 HDR despite the obstructions present while collecting the data.

Animal Husbandry Pavilion

In contrast to the Cushing Memorial Library registration reports, the Animal Husbandry Pavilion reports show less variance in terms of Maximum Point Error and Mean Point Error, however it shows more variance in the Minimum Overlap values among the three data sets. When comparing the three sets of values for this building, the Focus3D showed the tightest registration, in terms of Maximum Point Error and Mean Point Error, and the newest model, the Focus S 350, had the higher Minimum Overlap, as seen in Table 4.1 on the previous page of this study. Based on the obstructions discussed in section 4.2 of this study, and the lack of variance in those obstructions between data sets, the researcher is unsure of what caused this outcome. However, based on the comparison of these factors, the assessment indicates that the Focus3D data set, collected by the oldest of the three laser scanning systems, is the best in regards registration based on the factors that were assessed.

Y.M.C.A. Building

The registration reports of the YMCA building show similar results as those presented for the Cushing Memorial Library but in addition to the Focus S 350 having the highest values in regards to Maximum Point Error and Mean Point Error, it also has the lowest value in regards to Minimum Overlap.

Whereas the other two data sets, collected by the two older models, show similar results in regards to Mean Point Error and Minimum Overlap, and a slight variance in Maximum Point Error, as shown in Table 4.1 on page 52. It is the opinion of the researcher that these difference were due to the Y.M.C.A. Building being the most affected by overhanging tree branches, and the presence of more landscaping obstructions when compared to the other buildings. Therefore, based on the values shown, the data set collected by the oldest model, the Focus3D, was the best data set of the three due to its tighter registration values and higher percentage of overlap present.

4.4. Aligned Registration Report Comparison

The registered point clouds created from each data set were aligned by the process discussed in section 3.7 of this study. Because the point clouds used in this step of analysis were exported as .e57 files from each of the individual project files that were originally created, the previously mentioned registration values of each point cloud data set was not affected during this additional registration process. Once registered using the settings mentioned, registration reports for the aligned data sets were exported from SCENE to assess how similar, or how different, each of the data sets for each given building were. These results are summarized in Table 4.2 that is shown on the next page. The full reports are available in Appendix B of this study.

Table 4.2 – FARO SCENE alignment registration report summary

Summary of Aligned Registration Reports - FARO SCENE		
Building	**Category**	**Data**
Cushing Memorial Library	Laser Scanner Model	All
	Number of Scans	3 Scans
	Maximum Point Error	3.6 mm
	Mean Point Error	3.0 mm
	Minimum Overlap	95.1%
Animal Husbandry Pavilion	Laser Scanner Model	All
	Number of Scans	3 Scans
	Maximum Point Error	3.3 mm
	Mean Point Error	3.2 mm
	Minimum Overlap	95.8%
Y.M.C.A. Building	Laser Scanner Model	All
	Number of Scans	3 Scans
	Maximum Point Error	2.9 mm
	Mean Point Error	2.4 mm
	Minimum Overlap	97.1%

Cushing Memorial Library

The registration report based on the cloud to cloud registration, or alignment, of the three point cloud data sets that were created for the Cushing Memorial Library show a very tight alignment. As shown above in Table 4.2, and in Appendix B, the Maximum Point Error was 3.6 mm with a Mean Point Error of 3.0 mm indicating that the various point clouds are very similar. The Minimum Overlap value of 95.1% further exemplifies this similarity between data sets. Based on the analysis provided in section 4.2 and section 4.3 of this study, the variance shown is likely due to the obstructions that were present in the data gathering process, such as the orange temporary fencing and parked trailer are shown in Figure 4.1 on page 48 of this study.

Animal Husbandry Pavilion

Similarly to the Cushing Memorial Library, the Animal Husbandry Pavilion data sets aligned very tightly. As shown in Table 4.2 on the previous page, and in Appendix B, the Maximum Point Error was 3.3 mm and the Mean Point Error was 3.2 mm, which indicates that the various point clouds are very consistent and aligned even tighter than the Cushing Memorial Library data sets. The Minimum Overlap value of 95.8% further expresses this consistency. Based on the visual comparison conduced in section 4.2 of this study, the slight variances shown are likely due to the vehicle traffic that caused temporary obstructions during the data gathering process.

Y.M.C.A. Building

The Y.M.C.A. Building showed the tightest registration values among the building data sets collected by each laser scanning system, even though they had the loosest registration values in the individual data sets themselves. Despite the discouraging individual data set registration values, the aligned data set showed a Maximum Point Error of 2.9 mm, a Mean Point Error of 2.4 mm, and a Minimum Overlap of 97.1%. Although this was surprising at first, the research indicates that these findings are accurate based on the lack of major obstructions when gathering data on this specific building. In contrast to the larger obstructions such as vehicles and fencing that were present during the data collection for the Cushing Memorial Library and Animal Husbandry Pavilion data sets, the only major obstructions during the collection of data for the Y.M.C.A. building were the landscaping elements.

4.5. Analysis of Feature Measurements

In order to analyze the similarities and differences in the data sets in more detail, the researcher conducted a series of measurements on features present on each of the buildings primary facades. Four types of measurements were collected on each building: a horizontal measurement on each façade, a vertical measurement on each façade, a diagonal measurement on each façade, and a volumetric measurement between two façades. The features measured varied in size and location in an effort to empirically show the similarities, or differences, in each point cloud data set being analyzed. The researcher collected 33 measurements from each of the laser scanning systems, for a total of 99 measurements. The measurements ranged in distance from 0.9018 m to 68.7259 meters with eleven (33.33%) of the measurements under 5 m in length, fifteen (45.46%) of the measurements between 5 – 15 m in length, and the remaining seven (21.21%) measurements being longer than 15 m in length.

Each of the collected measurements was then compared to the corresponding measurements collected by the other two laser scanning systems to calculate a delta, or difference, between each pair of measurements. For each of the 33 measurement locations the following delta values were calculated: Focus3D vs. Focus3D x330 HDR, Focus3D vs. Focus S 350, and Focus3D x330 HDR vs. Focus S 350. This processes resulted in the calculation of 99 delta values that will be discussed in the remainder of this section. In addition to these individual delta values that were calculated, the researcher also calculated the average delta of each pair of laser scanning systems being compared, and the overall average delta of all three comparisons. A summary of the measurements and calculations are provided below in Table 4.3. Orthographic and Isometric views of the measurements are provided in Appendix C.

Table 4.3 – Summary of feature measurements and calculated deltas

Measurement Details				Measured Point to Point Distance (m)				Calculated Delta (mm)			
Building	Façade Measured	Measurement #	Measurement Type	(A) Focus 3D	(B) Focus x330 HDR	(C) Focus s350	Average (m)	A - B	A - C	B - C	Average
Cushing Memorial Library	Northwest	1	Horizontal	7.1855	7.1822	7.1813	7.1830	3.30	4.20	0.90	2.80
		2	Vertical	1.9575	1.9557	1.9567	1.9566	1.80	0.80	1.00	1.20
		3	Diagonal	8.1706	8.1703	8.1723	8.1711	0.30	1.70	2.00	1.33
	Southwest	4	Horizontal	2.7750	2.7731	2.7735	2.7739	1.90	1.50	0.40	1.27
		5	Vertical	8.1228	8.1230	8.1241	8.1233	0.20	1.30	1.10	0.87
		6	Diagonal	11.9015	11.9007	11.9007	11.9010	0.80	0.80	0.00	0.53
	Southeast	7	Horizontal	6.3121	6.3147	6.3099	6.3122	2.60	2.20	4.80	3.20
		8	Vertical	3.6533	3.6513	3.6512	3.6519	2.00	2.10	0.10	1.40
		9	Diagonal	1.1763	1.1728	1.1745	1.1745	3.50	1.80	1.70	2.33
	Northwest-Southeast	10	Volumetric	38.1551	38.1514	38.1548	38.1538	3.70	0.30	3.40	2.47
Animal Husbandry Pavilion	Northwest	11	Horizontal	3.7989	3.7980	3.7975	3.7981	0.90	1.40	0.50	0.93
		12	Vertical	5.2213	5.2227	5.2212	5.2217	1.40	0.10	1.50	1.00
		13	Diagonal	12.2049	12.2032	12.2086	12.2056	1.70	3.70	5.40	3.60
	Southwest	14	Horizontal	0.9018	0.9027	0.9031	0.9025	0.90	1.30	0.40	0.87
		15	Vertical	7.1763	7.1794	7.1785	7.1781	3.10	2.20	0.90	2.07
		16	Diagonal	2.1714	2.1749	2.1706	2.1723	3.50	0.80	4.30	2.87
	Southeast	17	Horizontal	47.4952	47.4966	47.4978	47.4965	1.40	2.60	1.20	1.73
		18	Vertical	1.9947	1.996	1.9965	1.9957	1.30	1.80	0.50	1.20
		19	Diagonal	18.449	18.4489	18.4441	18.4473	0.10	4.90	4.80	3.27
	Northeast	20	Horizontal	5.7122	5.7191	5.7137	5.7150	6.90	1.50	5.40	4.60
		21	Vertical	2.4430	2.4454	2.4412	2.4432	2.40	1.80	4.20	2.80
		22	Diagonal	9.8699	9.8749	9.8737	9.8728	5.00	3.80	1.20	3.33
	Northwest-Southeast	23	Volumetric	68.7259	68.7201	68.7231	68.7230	5.80	2.80	3.00	3.87
Y.M.C.A Building	Northwest	24	Horizontal	1.8049	1.8076	1.8093	1.8073	2.70	4.40	1.70	2.93
		25	Vertical	11.0127	11.0085	11.0070	11.0094	4.20	5.70	1.50	3.80
		26	Diagonal	14.6101	14.6107	14.6124	14.6111	0.60	2.30	1.70	1.53
	Southwest	27	Horizontal	28.8772	28.8785	28.8803	28.8787	1.30	3.10	1.80	2.07
		28	Vertical	3.5228	3.5197	3.5183	3.5203	3.10	4.50	1.40	3.00
		29	Diagonal	5.6358	5.6381	5.6332	5.6357	2.30	2.60	4.90	3.27
	Southeast	30	Horizontal	6.0029	6.0040	6.0054	6.0041	1.10	2.50	1.40	1.67
		31	Vertical	5.3446	5.3425	5.3480	5.3450	2.10	3.40	5.50	3.67
		32	Diagonal	15.3834	15.3841	15.3873	15.3849	0.70	3.90	3.20	2.60
	Northwest-Southeast	33	Volumetric	37.2539	37.2584	37.2629	37.2584	4.50	9.00	4.50	6.00

Average Delta (mm)			
A - B	A - C	B - C	Overall
2.34	2.63	2.31	2.43

<u>Focus3D vs. Focus3D x330 HDR</u>

The calculated differences, or deltas, between the measurements collected from the Focus3D and Focus3D x330 HDR point clouds ranged from

0.10 mm and 6.90 mm. Of those 33 calculated deltas, seventeen (52.52%) were under 2 mm, eleven (33.33%) were between 2 – 4 mm, and the remaining five (15.15%) were greater than 4 mm. The average calculated delta between the two data set measurements was 2.34 mm. These results indicate there was no significant difference between the point cloud data sets collected.

Focus3D vs. Focus S 350

When comparing the calculated deltas between the point cloud data sets created by the Focus3D and Focus S 350 laser scanning systems, the values ranged from 0.10 mm and 9.00 mm, with an average delta of 2.63 mm. Fourteen (42.42%) of the 33 calculated deltas were under 2 mm, thirteen (39.39%) of the them were between 2 – 4 mm, and the remaining six (18.18%) were greater than 4 mm. Despite the largest delta of 9.00 mm, which was based on a measured difference of just over 37 m, this data indicates that there were no major differences between the data sets collected by the two laser scanner systems.

Focus3D x330 HDR vs. Focus S 350

Of all three laser scanner systems being compared the Focus3D x330 HDR and Focus S 350 comparison had what the researcher would consider to be the most interesting results. The range of the 33 calculated deltas was 0.00 m to 5.50 mm with twenty-one (63.64%) of them being under 2 mm, three (9.09%) between 2 – 4 mm, the remaining nine (27.27%) being greater than 4 mm, and the average calculated delta was 2.31 mm. The reason the researcher found this data set comparison to be the most interesting is because of three factors. First, the minimum calculated delta of 0.00 mm, based on measurements to the fourth decimal place, was on a distance between features of just under 12 m. Second, the data set was split more than both of the other two comparisons in regards to the calculated deltas under 2 mm and those greater than 4 mm, with the least number of results being between 2 – 4 mm. Of the 33 calculated deltas 90.91% fell into the categories of under 2 mm or greater than 4 mm, whereas the other two comparisons resulted in at least 33.33% of the calculated deltas falling into the middle range of 2 – 4 mm. Despite this split, the analysis indicates that there was no significant difference in the two data sets given that the average calculated delta was 2.31 mm.

Overall Average Delta

When combining all three sets of the calculated delta values, for a total of 99 delta values, there is a range of 0.00 mm to 9.00 mm, with an overall average calculated delta of 2.43 mm. Of those 99 calculated deltas 52 (52.53%) were under 2 mm, 27 (27.27%) were between 2 – 4 mm, and 20 (20.20%) were greater than 4 mm. Given that nearly 80% of the values calculated were under 4 mm in length, and with the average calculated delta of just 2.43 mm, the results the this study suggest that there is no significant difference between any of the three data sets, despite the 9.00 mm delta value that was calculated in the comparison of the Focus3D and Focus S 350 laser scanning systems. Had the 9.00 mm value been calculated on a measurement of a shorter distance, and not a measurement over 37 m in length, more research would be necessary.

4.6. Endnotes

1. Faro Technologies, FARO Laser Scanner Focus3D Tech Sheet, April 2013: 4. https://faro.app.box.com/s/rn5ybokxh09c8nabdfeaxzx7v91qg9t9.

2. Faro Technologies, FARO Laser Scanner Focus3D X 330 HDR Tech Sheet, April 2016: 2. https://faro.app.box.com/s/dd1af36zjlkhoabqdff4iw9xbd11puw5/file/6099377372.

3. Faro Technologies, FARO Laser Scanner Focus S 350 Tech Sheet, October 2016: 2. https://faro.app.box.com/s/kmfsfx34aqdigv4wippqvsr02e4ayjn0/file/303605294993.

4. Faro Technologies, FARO Laser Scanner Focus3D User Manual, November 2018: 153. https://faro.app.box.com/s/8xtj92jnpu011i8crn2qyh1bd6d3s0mo/file/405611057377

5. Faro Technologies, FARO Laser Scanner Focus S 350 Tech Sheet, October 2016: 2. https://faro.app.box.com/s/kmfsfx34aqdigv4wippqvsr02e4ayjn0/file/303605294993.

5. CONCLUSIONS

5.1. Summary of Results

As discussed in the literature review of this study, there is an ever growing need for high quality documentation of our local, national, and global heritage sites in the ever changing world that we all live in. Whether it stems from circumstances related to natural phenomenon or those caused by humans, we often have little to no warning or indication of when a disaster will occur at one of our heritage sites that could result in the total loss of that site or structure. Because of this it is more important than ever that we utilize the digital tools available to us in collecting high quality data on these sites and structures. Over the past few decades one tool that has become more and more prevalent in this process is the three dimensional laser scanners. Because of their ability to collect a large quantity of highly accurate data in a relatively short period of time, and the freedom they provide in analyzing and interpreting the data collected in many different methods and formats, they have become a mainstay in the heritage documentation world.

However, making the choice to utilize a laser scanning system in the documentation process is only the first step. Because of the number of available choices on the market, ranging from stationary terrestrial systems such as those utilized in this study to mobile/portable systems such as those contained in a backpack, selecting a system that meets the needs of the project or site can often be difficult for those involved as there are many factors to take into consideration. These factors, or needs, should be clearly defined from the start of a project because the individuals conducting the documentation, or their managing entities, have to not only choose between various hardware and software types and providers, they also have the choose whether or not to utilize a system that is brand new, or one that is older or even used. Because funding limitations are often a major factor in these decisions, given the lack of philanthropy directed towards heritage sites[1], as discussed in section 1.1 of this study, those involved may not have the ability to select the latest and greatest system due to cost, and therefore their only option may be to utilize an older system, or one that is used. Given these all too common limitations, this study sought to answer the question, do you need the newest hardware system that is available, or can you utilize an older hardware system and rely on current software to achieve similar results?

Based on the analysis provided in section 4 of this study, which compared the results of three different phase shift terrestrial laser scanning hardware systems that have been released over the last decade from a single manufacturer, the results of this study suggest that as long as current software is used in registering and processing the data, there is no significant difference in results no matter which hardware system is utilized. As discussed in section 4.2, the only major visual differences in the data sets collected were caused by obstructions that were not consistent between data sets.

Additionally, the registration reports presented in section 4.3 and section 4.4 of this study indicate that there is no distinct connection between how new a system is, and how well the data collected with the system will register in creating the resulting point cloud. As shown in Table 4.2 on page 55, when each of the data sets for a given point cloud were aligned as a group, there was a maximum point error of 3.6 mm, and a minimum overlap among all alignments of 95.1%, which indicates that there is no significant difference between the data sets collected. Furthermore, when comparing the point cloud data sets through the measurement of distinct façade features, as discussed in section 4.5 of the study, no significant difference was observed. As shown in Table 4.3, on page 58, the 99 measurements collected and the resulting 99 delta values that were calculated resulted in an overall average delta of just 2.43 mm.

Based on these results and the analysis conducted, this study suggests that the use of older hardware systems are capable of providing registered point cloud data sets with no significant observable differences when compared with data sets collected by newer laser scanner systems or models, as long as the data collected is processed and registered using current software programs that are available. Therefore, should the use of a three dimensional laser scanner meet the needs of a documentation project, and be financially feasible, it is the recommendation of the researcher that it be utilized so that should the need arise to repair, reconstruct, or rehabilitate a heritage site due to man-made or natural phenomena there is adequate highly accurate data available to do so.

5.2. Limitations

As with any study there were certain limitations that were present throughout the process. For this study the researcher has identified three general areas of limitations: the scope of the study, the methodology used in the study, and the duration or timing of the study. First, in regards to the scope of the study, it was limited to a select line of laser scanning systems, from a single manufacture. Second, when processing and registering the point cloud data sets, the researcher chose to use a methodology that utilized the manufacturer default settings within the selected software package. Third, given the duration of time that passed between the initial collection of data by the Focus3D laser scanning system and the subsequent data collected by the Focus3D x330 HDR and Focus S 350 laser scanning systems, there was significant growth in landscaping elements such as trees, bushes, and other ground bases shrubbery.

The limitations based on the scope of the study are important to note because there are numerous terrestrial three dimensional laser scanning systems that could have been selected and utilized in the study. The terrestrial three dimensional laser scanning systems selected for this study were chosen for two primary reasons; one, their prevalence in the documentation community, and two, their availability to the researcher as discussed in section 3.3 of this study.

In regards to the limitations of the methodology, there are three variables that should be noted. Regarding the use of the manufacturer default settings being utilized when processing and registering the point cloud data sets, based on the researchers experience this could limit the resulting point clouds in terms of the registration values, however that result is not certain. The reason that the researcher proceeded in this fashion was based on the idea that not everyone who might be utilizing these laser scanning systems is an expert user, or even experienced user, and therefore may not be capable or comfortable with manipulating the software program settings when processing and registering the data to curate tighter registration results. Based on the researcher's experience with the software over the period of the last 7+ years, the use of the default settings often produce an outcome that are on par with those possible through the manipulation of the software settings.

Additionally, in regards to the methodology, specifically the measurements collected to compare each of the individually registered point cloud data sets between each of the laser scanning systems, there is an element of human error that could not be avoided, but could be limited. To reduce these possible errors, the researcher selected features and points that were distinct, or sharp, corners when possible and avoided the used of rounder or undefined features.

Furthermore, the variables impacting the data collection process, such as the obstructions discussed in section 4.2 of this study, might have been avoidable with a change in methodology, however, given the consistent construction taking place on campus, and year round classes that are offered, there is no guarantee that this would have improved the situation and avoided all obstructions. This is to be expected in a study being conducted in the field and not a controlled experiment conducted in a lab setting.

Lastly, and possibly the biggest limitation of the study, was the passing of time that occurred between the initial data set being collected in 2015, and the two subsequent data sets that were collected in 2019. As discussed in section 3.3 of this study, many of the obstructions that were observed were caused by landscaping elements that were present around the exterior of the buildings that were documented. This is important to note because as time passed, a period of 4 years, those elements such as trees, bushes, and other ground based shrubbery continued to mature and grow around the buildings being documented. Because of this growth, when data was collected with the two newer scanners, the Focus3D x330 HDR and the Focus S 350, there was a possibility of a larger obstruction than what was previously observed in the original collection of data by the Focus3D. Due to these changes the researcher made the decision to only compare the point cloud data of the actual building facades, and not the entire landscape surrounding the buildings, to avoid as much of this change as possible. Although these changes still caused some variance between data sets, the study indicates that the changes were not significant enough to cause substantial changes in the final outputs of the data sets in the form of registered point clouds.

5.3. Recommendations on Future Research

Given the limitations of this study that were discussed in section 5.2 the researcher has five suggestions regarding future research that is related to this study. First, this researcher suggests the use of multiple forms of laser scanning systems, from multiple manufactures. Although those utilized in this study represent a significant portion of the laser scanners being utilized in documentation efforts such as those undertaken in this study, these systems are being improved upon constantly and new systems are being introduced to the market at an ever increasing rate. Additionally, including a larger variety of scanning systems, and/or manufacturers, would allow for future researchers to compare results across those systems, which could lead to additional findings and conclusions. One such comparison that would relate directly to this study, in regards to the financial constraints that were discussed, would be the inclusion of the Leica BLK 360 system given its reduced cost in comparison to the systems utilized.

The second recommendation for future research would be to include the use of multiple software programs in the processing and registration of the collected data as each software program uses different algorithms and methods of connecting the various data sets. As only one software program was used in this study there is a possibility that other software programs, such as Autodesk

ReCap Pro, might produce different results. The researcher conducted a test using the data set collected by the Focus S 350 on the Y.M.C.A. Building, the lowest quality set of data in the opinion of the researcher, and Autodesk ReCap Pro was not able to register the scans together using the default manufacture settings. However, as the remaining data sets were not run, more research would be needed to determine if there would be value added by utilizing the additional software programs.

Third, additional building forms and building materials could be included and assessed in a related study. As the building facades in this study primarily consisted of brick, cast stone, metal, and glass, it would be beneficial for future research to include other materials commonly found in historic buildings and sites such as wood and natural stone. The inclusion of these materials would help to provide a broader set of results and could lead to additional findings based on the differentiation of materials and their given properties.

The fourth suggestion for future research would be to conduct a study utilizing only the intensity values, and not the colorized scans, recorded by the various laser scanning systems. As intensity values are recorded directly from the return of the laser on each measurement there is a possibility that the scans would register better than they have using the fully colorized scan data that was utilized in this study. The researcher conducted a test of this theory using the data collected by the Focus3D x330 HDR on the Cushing Memorial Library, which the researcher considers the best data set of the group, and the registration report showed interesting results. As discussed earlier in this study the registration report using the fully colorized scans resulted in a Maximum Point Error of 3.9 mm, a Mean Point Error of 2.8 mm and a Minimum Overlap of 27.2%. When the data was run without color, using only the intensity values for the registration process, the results indicated a Maximum Point Error of 3.4 mm, a Mean Point Error of 2.5 mm, and a Minimum Overlap of 23.6%. Given the improvement in the Maximum Point Error and Mean Point Error, it is the opinion of the researcher that further investigation could be beneficial in better understanding the best practices that are possible in the registration process.

Lastly, it is the suggestion of this researcher that future research be completed utilizing a methodology that performs the data collection process in a time frame that is much shorter than that used in this study. By doing this future researchers would avoid issues such as substantial grown of landscaping elements, or changes to the buildings being documented.

5.4. Endnotes

1. Global Heritage Fund, *Saving Our Vanishing Heritage: Safeguarding Endangered Cultural Heritage Sites in the Developing World* (2010): 8. http://globalheritagefund.org/images/uploads/docs/GHFSavingOurVanishingHeritagev1.0singlepageview.pdf.

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APPENDIX A

Individual Registration Reports

Figure A.01 - Registration Report: Cushing Memorial Library – FARO SCENE – Focus3D

Registration Report

Project	Cushing
Cluster	Scans
Recording Period	6/9/2015, 8:44:06 AM - 6/9/2015, 11:02:55 AM
Location	
Report Date	9/19/2019, 4:22:12 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	5.1 mm
Mean Point Error	2.8 mm
Minimum Overlap	26.0 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
Cushing002	3	5.1	3.1	26.0 %
Cushing003	3	3.0	2.6	44.4 %
Cushing004	4	5.1	3.8	26.0 %
Cushing005	2	3.9	3.0	77.6 %
Cushing007	3	3.2	2.9	35.3 %
Cushing008	3	3.2	2.7	35.3 %
Cushing010	2	2.6	2.1	70.7 %
Cushing011	2	2.3	1.9	67.5 %
Cushing001	2	2.3	2.0	66.0 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
Cushing002	Cushing003	2.6	79.4 %
Cushing002	Cushing004	5.1	26.0 %
Cushing004	Cushing003	3.0	44.4 %
Cushing005	Cushing004	3.9	77.6 %
Cushing005	Cushing007	2.2	78.3 %
Cushing007	Cushing004	3.1	48.3 %
Cushing007	Cushing008	3.2	35.3 %
Cushing008	Cushing010	2.6	70.7 %
Cushing008	Cushing011	2.3	67.5 %
Cushing011	Cushing010	1.5	89.8 %
Cushing001	Cushing002	1.7	87.3 %
Cushing001	Cushing003	2.3	66.0 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
Cushing005	Cushing005	0.0078
Cushing007	Cushing007	0.0079
Cushing001	Cushing001	0.0243
Cushing002	Cushing002	0.0127
Cushing008	Cushing008	0.0146
Cushing004	Cushing004	0.0093
Cushing003	Cushing003	0.0091
Cushing011	Cushing011	0.0049
Cushing010	Cushing010	0.0255

Figure A.02 - Registration Report: Cushing Memorial Library – FARO SCENE – Focus3D x330 HDR

Registration Report

Project	Cushing_330
Cluster	Scans
Recording Period	1/1/2002, 12:12:04 AM - 1/1/2002, 1:23:19 AM
Location	
Report Date	9/19/2019, 4:22:58 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	3.9 mm
Mean Point Error	2.8 mm
Minimum Overlap	27.2 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
Cushing_330007	3	2.9	2.6	33.0 %
Cushing_330008	2	2.2	2.0	64.5 %
Cushing_330009	2	2.7	2.2	56.2 %
Cushing_330001	2	3.1	2.3	62.1 %
Cushing_330002	3	3.3	2.2	27.2 %
Cushing_330003	4	3.9	3.1	31.3 %
Cushing_330004	4	3.4	3.3	27.2 %
Cushing_330005	3	3.9	3.5	31.3 %
Cushing_330006	3	3.6	3.3	33.0 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
Cushing_330007	Cushing_330008	2.2	64.5 %
Cushing_330007	Cushing_330006	2.9	33.0 %
Cushing_330009	Cushing_330007	2.7	56.2 %
Cushing_330009	Cushing_330008	1.8	72.3 %
Cushing_330001	Cushing_330002	1.4	80.8 %
Cushing_330003	Cushing_330001	3.1	62.1 %
Cushing_330003	Cushing_330002	2.0	79.2 %
Cushing_330004	Cushing_330002	3.3	27.2 %
Cushing_330004	Cushing_330003	3.4	47.3 %
Cushing_330004	Cushing_330005	3.0	78.7 %
Cushing_330004	Cushing_330006	3.3	59.2 %
Cushing_330005	Cushing_330003	3.9	31.3 %
Cushing_330005	Cushing_330006	3.6	78.8 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
Cushing_330009	Cushing_330009	0.0097
Cushing_330007	Cushing_330007	0.0117
Cushing_330004	Cushing_330004	0.0116
Cushing_330005	Cushing_330005	0.0102
Cushing_330003	Cushing_330003	0.0114
Cushing_330008	Cushing_330008	0.0218
Cushing_330001	Cushing_330001	0.0137
Cushing_330006	Cushing_330006	0.0171
Cushing_330002	Cushing_330002	0.0093

Figure A.03 - Registration Report: Cushing Memorial Library – FARO SCENE – Focus S 350

Registration Report

Project	Cushing_350
Cluster	Scans
Recording Period	4/15/2019, 3:11:37 PM - 4/15/2019, 4:23:54 PM
Location	
Report Date	9/19/2019, 4:24:27 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	8.0 mm
Mean Point Error	4.6 mm
Minimum Overlap	28.3 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
Scan_008	3	8.0	4.9	28.3 %
Scan_001	2	5.9	4.6	31.6 %
Scan_002	2	3.4	3.3	45.3 %
Scan_003	3	5.9	4.9	31.6 %
Scan_004	3	5.4	4.3	37.2 %
Scan_005	2	3.3	3.2	69.1 %
Scan_006	4	8.0	5.6	28.3 %
Scan_007	3	6.5	5.3	42.1 %
Scan_009	2	5.6	4.3	62.7 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
Scan_008	Scan_009	2.9	78.9 %
Scan_008	Scan_007	3.9	77.6 %
Scan_008	Scan_006	8.0	28.3 %
Scan_001	Scan_002	3.2	64.0 %
Scan_001	Scan_003	5.9	31.6 %
Scan_003	Scan_002	3.4	45.3 %
Scan_003	Scan_004	5.4	37.2 %
Scan_004	Scan_005	3.1	71.1 %
Scan_006	Scan_004	4.5	46.8 %
Scan_006	Scan_005	3.3	69.1 %
Scan_006	Scan_007	6.5	42.1 %
Scan_009	Scan_007	5.6	62.7 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
Scan_008	Scan_008	0.0152
Scan_006	Scan_006	0.0097
Scan_001	Scan_001	0.0056
Scan_009	Scan_009	0.0150
Scan_003	Scan_003	0.0081
Scan_007	Scan_007	0.0163
Scan_002	Scan_002	0.0058
Scan_004	Scan_004	0.0130
Scan_005	Scan_005	0.0083

Figure A.04 - Registration Report: Animal Husbandry Pavilion – FARO SCENE – Focus3D

Registration Report

Project	Pavilion
Cluster	Scans
Recording Period	6/23/2015, 9:55:14 AM - 6/23/2015, 1:43:32 PM
Location	
Report Date	9/19/2019, 4:25:46 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	6.6 mm
Mean Point Error	3.0 mm
Minimum Overlap	15.7 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
New_Project_Scan_008	4	3.9	3.3	29.3 %
New_Project_Scan_009	4	3.5	2.8	39.6 %
New_Project_Scan_010	5	4.3	3.0	27.0 %
New_Project_Scan_011	4	3.9	3.1	29.3 %
New_Project_Scan_013	4	3.3	2.8	29.3 %
New_Project_Scan_014	4	3.6	2.5	15.7 %
New_Project_Scan_015	3	2.3	1.8	61.7 %
New_Project_Scan_016	4	3.0	2.7	30.1 %
New_Project_Scan_017	5	4.9	3.7	27.0 %
New_Project_Scan_001	4	3.6	2.8	15.7 %
New_Project_Scan_002	4	3.0	2.6	26.5 %
New_Project_Scan_003	4	3.1	2.6	39.8 %
New_Project_Scan_004	5	6.6	3.6	23.9 %
New_Project_Scan_005	4	3.5	2.8	39.8 %
New_Project_Scan_006	4	4.9	3.2	26.3 %
New_Project_Scan_007	4	6.6	3.6	23.9 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
New_Project_Scan_008	New_Project_Scan_017	3.4	51.1 %
New_Project_Scan_008	New_Project_Scan_011	3.9	29.3 %
New_Project_Scan_009	New_Project_Scan_008	2.6	75.7 %
New_Project_Scan_009	New_Project_Scan_017	3.5	39.6 %
New_Project_Scan_009	New_Project_Scan_011	2.7	44.7 %
New_Project_Scan_010	New_Project_Scan_008	3.1	70.3 %
New_Project_Scan_010	New_Project_Scan_009	2.2	78.4 %
New_Project_Scan_010	New_Project_Scan_011	2.3	54.8 %
New_Project_Scan_010	New_Project_Scan_017	4.3	27.0 %
New_Project_Scan_010	New_Project_Scan_013	3.2	29.3 %
New_Project_Scan_013	New_Project_Scan_011	3.3	45.2 %
New_Project_Scan_014	New_Project_Scan_013	2.7	37.1 %
New_Project_Scan_014	New_Project_Scan_016	2.7	42.3 %
New_Project_Scan_014	New_Project_Scan_001	3.6	15.7 %
New_Project_Scan_015	New_Project_Scan_013	2.1	61.7 %
New_Project_Scan_015	New_Project_Scan_014	1.0	98.8 %
New_Project_Scan_015	New_Project_Scan_016	2.3	71.4 %
New_Project_Scan_016	New_Project_Scan_002	3.0	30.1 %
New_Project_Scan_001	New_Project_Scan_016	2.6	44.9 %
New_Project_Scan_001	New_Project_Scan_002	2.5	79.7 %
New_Project_Scan_001	New_Project_Scan_003	2.5	49.8 %
New_Project_Scan_003	New_Project_Scan_002	2.2	75.1 %
New_Project_Scan_003	New_Project_Scan_005	3.1	39.8 %
New_Project_Scan_004	New_Project_Scan_002	2.8	26.5 %
New_Project_Scan_004	New_Project_Scan_003	2.5	67.1 %
New_Project_Scan_004	New_Project_Scan_005	2.3	59.0 %
New_Project_Scan_004	New_Project_Scan_007	6.6	23.9 %
New_Project_Scan_006	New_Project_Scan_017	4.9	30.7 %
New_Project_Scan_006	New_Project_Scan_004	3.6	26.3 %
New_Project_Scan_006	New_Project_Scan_005	2.2	44.1 %
New_Project_Scan_006	New_Project_Scan_007	2.2	60.4 %
New_Project_Scan_007	New_Project_Scan_017	2.2	48.0 %
New_Project_Scan_007	New_Project_Scan_005	3.5	47.1 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
New_Project_Scan_010	New_Project_Scan_010	0.0175
New_Project_Scan_006	New_Project_Scan_006	0.0066
New_Project_Scan_015	New_Project_Scan_015	0.0075
New_Project_Scan_004	New_Project_Scan_004	0.0173
New_Project_Scan_009	New_Project_Scan_009	0.0217
New_Project_Scan_014	New_Project_Scan_014	0.0098
New_Project_Scan_008	New_Project_Scan_008	0.0089
New_Project_Scan_001	New_Project_Scan_001	0.0233
New_Project_Scan_013	New_Project_Scan_013	0.0084
New_Project_Scan_007	New_Project_Scan_007	0.0210
New_Project_Scan_003	New_Project_Scan_003	0.0202
New_Project_Scan_005	New_Project_Scan_005	0.0027
New_Project_Scan_011	New_Project_Scan_011	0.0152
New_Project_Scan_017	New_Project_Scan_017	0.0205
New_Project_Scan_016	New_Project_Scan_016	0.0201
New_Project_Scan_002	New_Project_Scan_002	0.0111

Figure A.05 - Registration Report: Animal Husbandry Pavilion – FARO SCENE – Focus3D x330 HDR

Registration Report

Project	Pavilion330v2
Cluster	Scans
Recording Period	1/1/2002, 12:13:02 AM - 1/1/2002, 2:12:13 AM
Location	
Report Date	9/19/2019, 4:26:38 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	7.4 mm
Mean Point Error	3.6 mm
Minimum Overlap	12.5 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
Pav330001	4	6.7	4.1	29.1 %
Pav330002	4	4.1	3.1	43.4 %
Pav330003	4	5.8	4.3	37.7 %
Pav330004	4	4.9	3.6	37.1 %
Pav330005	4	4.4	3.0	33.3 %
Pav330006	4	3.5	2.2	35.8 %
Pav330007	4	3.4	2.5	42.4 %
Pav330008	5	4.4	2.9	26.2 %
Pav330009	4	3.4	2.7	41.1 %
Pav330010	5	7.4	3.9	12.5 %
Pav330011	2	3.1	2.7	41.1 %
Pav330012	3	3.9	3.5	24.0 %
Pav330013	4	7.4	4.9	12.5 %
Pav330014	4	6.7	4.4	29.1 %
Pav330015	5	6.7	5.0	26.1 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
Pav330002	Pav330001	2.3	79.6 %
Pav330002	Pav330003	2.8	82.8 %
Pav330002	Pav330015	4.1	46.2 %
Pav330002	Pav330004	3.1	43.4 %
Pav330003	Pav330001	3.6	69.3 %
Pav330003	Pav330004	4.9	54.5 %
Pav330004	Pav330005	2.9	58.1 %
Pav330004	Pav330006	3.5	37.1 %
Pav330005	Pav330007	3.4	48.5 %
Pav330006	Pav330005	1.5	65.5 %
Pav330006	Pav330007	1.5	53.0 %
Pav330008	Pav330005	4.4	33.3 %
Pav330008	Pav330006	2.2	35.8 %
Pav330008	Pav330007	1.6	64.3 %
Pav330008	Pav330010	4.2	26.2 %
Pav330009	Pav330007	3.4	42.4 %
Pav330009	Pav330008	2.3	64.4 %
Pav330009	Pav330010	2.0	78.1 %
Pav330009	Pav330011	3.1	41.1 %
Pav330010	Pav330011	2.2	83.0 %
Pav330010	Pav330013	7.4	12.5 %
Pav330012	Pav330010	3.9	24.0 %
Pav330012	Pav330013	2.8	82.2 %
Pav330012	Pav330014	3.8	43.0 %
Pav330013	Pav330015	6.7	26.1 %
Pav330014	Pav330001	6.7	29.1 %
Pav330014	Pav330013	2.7	72.1 %
Pav330014	Pav330015	4.5	68.3 %
Pav330015	Pav330001	3.9	59.5 %
Pav330015	Pav330003	5.8	37.7 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
Pav330002	Pav330002	0.0098
Pav330009	Pav330009	0.0055
Pav330008	Pav330008	0.0027
Pav330012	Pav330012	0.0020
Pav330010	Pav330010	0.0104
Pav330014	Pav330014	0.0059
Pav330013	Pav330013	0.0271
Pav330015	Pav330015	0.0115
Pav330003	Pav330003	0.0427
Pav330004	Pav330004	0.0237
Pav330011	Pav330011	0.0186
Pav330006	Pav330006	0.0027
Pav330005	Pav330005	0.0049
Pav330001	Pav330001	0.0088
Pav330007	Pav330007	0.0019

Figure A.06 - Registration Report: Animal Husbandry Pavilion – FARO SCENE – Focus S 350

Registration Report

Project	pavilion_350
Cluster	Scans
Recording Period	5/13/2019, 9:21:52 AM - 5/13/2019, 11:39:55 AM
Location	
Report Date	9/19/2019, 4:27:12 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	8.0 mm
Mean Point Error	4.2 mm
Minimum Overlap	18.3 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
Scan_034	1	4.0	4.0	77.8 %
Scan_048	3	4.7	4.0	18.3 %
Scan_035	3	5.2	4.3	18.3 %
Scan_036	3	6.0	5.5	31.5 %
Scan_037	3	6.0	4.4	42.1 %
Scan_038	4	5.3	3.3	31.5 %
Scan_039	4	7.1	3.5	40.2 %
Scan_040	3	5.9	3.3	52.7 %
Scan_041	4	8.0	6.3	33.8 %
Scan_042	4	7.1	4.3	30.9 %
Scan_043	4	8.0	4.7	33.6 %
Scan_044	4	5.7	4.2	40.3 %
Scan_045	5	7.1	3.9	21.4 %
Scan_046	4	5.7	4.0	40.3 %
Scan_047	3	4.7	3.3	21.4 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
Scan_048	Scan_047	4.7	72.2 %
Scan_048	Scan_046	3.5	48.0 %
Scan_035	Scan_034	4.0	77.8 %
Scan_035	Scan_048	3.7	18.3 %
Scan_035	Scan_036	5.2	46.3 %
Scan_037	Scan_036	6.0	62.4 %
Scan_037	Scan_038	3.5	56.3 %
Scan_038	Scan_036	5.3	31.5 %
Scan_039	Scan_037	3.8	42.1 %
Scan_039	Scan_038	1.6	64.3 %
Scan_040	Scan_038	2.5	59.6 %
Scan_040	Scan_039	1.4	69.6 %
Scan_040	Scan_041	5.9	52.7 %
Scan_041	Scan_039	7.1	40.2 %
Scan_041	Scan_042	4.1	57.1 %
Scan_041	Scan_043	8.0	33.8 %
Scan_042	Scan_043	2.0	50.5 %
Scan_042	Scan_044	3.9	47.8 %
Scan_042	Scan_045	7.1	30.9 %
Scan_043	Scan_044	4.1	48.4 %
Scan_043	Scan_045	4.7	33.6 %
Scan_045	Scan_044	3.2	61.1 %
Scan_046	Scan_044	5.7	40.3 %
Scan_046	Scan_045	3.0	69.9 %
Scan_046	Scan_047	3.9	64.6 %
Scan_047	Scan_045	1.4	21.4 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
Scan_035	Scan_035	0.0130
Scan_040	Scan_040	0.0060
Scan_041	Scan_041	0.0144
Scan_042	Scan_042	0.1043
Scan_039	Scan_039	0.0069
Scan_043	Scan_043	0.0182
Scan_048	Scan_048	0.0094
Scan_046	Scan_046	0.0237
Scan_037	Scan_037	0.0227
Scan_038	Scan_038	0.0156
Scan_036	Scan_036	0.0413
Scan_034	Scan_034	0.0306
Scan_047	Scan_047	0.0233
Scan_045	Scan_045	0.0108
Scan_044	Scan_044	0.0312

Figure A.07 - Registration Report: Y.M.C.A. Building – FARO SCENE – Focus

Registration Report

Project	YMCA
Cluster	Scans
Recording Period	6/30/2015, 10:07:16 AM - 6/30/2015, 12:48:06 PM
Location	
Report Date	9/19/2019, 4:27:49 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	6.8 mm
Mean Point Error	3.3 mm
Minimum Overlap	14.0 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
YMCA_Scan_007	5	4.8	3.5	14.0 %
YMCA_Scan_008	5	3.8	2.7	16.1 %
YMCA_Scan_009	5	4.3	2.8	31.1 %
YMCA_Scan_010	4	6.4	4.2	31.1 %
YMCA_Scan_011	2	3.8	3.4	52.2 %
YMCA_Scan_012	3	6.4	4.4	33.6 %
YMCA_Scan_013	1	2.9	2.9	50.2 %
YMCA_Scan_014	4	2.9	2.7	26.1 %
YMCA_Scan_001	1	2.2	2.2	34.5 %
YMCA_Scan_002	2	2.3	2.3	34.5 %
YMCA_Scan_003	3	3.8	3.2	14.0 %
YMCA_Scan_004	4	6.8	4.7	16.1 %
YMCA_Scan_005	6	6.8	3.2	26.1 %
YMCA_Scan_006	5	4.1	2.7	14.6 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
YMCA_Scan_007	YMCA_Scan_008	2.4	46.5 %
YMCA_Scan_007	YMCA_Scan_004	4.8	34.4 %
YMCA_Scan_007	YMCA_Scan_005	2.6	32.3 %
YMCA_Scan_007	YMCA_Scan_006	4.1	14.6 %
YMCA_Scan_007	YMCA_Scan_003	3.8	14.0 %
YMCA_Scan_008	YMCA_Scan_005	2.4	51.4 %
YMCA_Scan_008	YMCA_Scan_009	2.2	48.3 %
YMCA_Scan_010	YMCA_Scan_009	4.3	31.1 %
YMCA_Scan_011	YMCA_Scan_010	3.0	52.2 %
YMCA_Scan_011	YMCA_Scan_012	3.8	64.7 %
YMCA_Scan_012	YMCA_Scan_010	6.4	33.6 %
YMCA_Scan_012	YMCA_Scan_013	2.9	50.2 %
YMCA_Scan_014	YMCA_Scan_009	2.6	41.6 %
YMCA_Scan_014	YMCA_Scan_010	2.9	56.4 %
YMCA_Scan_014	YMCA_Scan_006	2.2	54.6 %
YMCA_Scan_014	YMCA_Scan_005	2.9	26.1 %
YMCA_Scan_002	YMCA_Scan_001	2.2	34.5 %
YMCA_Scan_002	YMCA_Scan_003	2.3	40.2 %
YMCA_Scan_004	YMCA_Scan_008	3.8	16.1 %
YMCA_Scan_004	YMCA_Scan_003	3.5	43.7 %
YMCA_Scan_004	YMCA_Scan_005	6.8	32.4 %
YMCA_Scan_005	YMCA_Scan_009	2.4	47.2 %
YMCA_Scan_006	YMCA_Scan_008	2.9	35.0 %
YMCA_Scan_006	YMCA_Scan_009	2.4	48.8 %
YMCA_Scan_006	YMCA_Scan_005	1.9	64.0 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
YMCA_Scan_014	YMCA_Scan_014	0.0184
YMCA_Scan_007	YMCA_Scan_007	0.0134
YMCA_Scan_011	YMCA_Scan_011	0.0067
YMCA_Scan_006	YMCA_Scan_006	0.0139
YMCA_Scan_002	YMCA_Scan_002	0.0092
YMCA_Scan_004	YMCA_Scan_004	0.0237
YMCA_Scan_003	YMCA_Scan_003	0.0086
YMCA_Scan_012	YMCA_Scan_012	0.0218
YMCA_Scan_010	YMCA_Scan_010	0.0236
YMCA_Scan_013	YMCA_Scan_013	0.0205
YMCA_Scan_008	YMCA_Scan_008	0.0084
YMCA_Scan_005	YMCA_Scan_005	0.0164
YMCA_Scan_001	YMCA_Scan_001	0.0218
YMCA_Scan_009	YMCA_Scan_009	0.0172

Figure A.08 - Registration Report: Y.M.C.A. Building – FARO SCENE – Focus3D x330 HDR

Registration Report

Project	YMCA_330
Cluster	Scans
Recording Period	1/1/2002, 12:15:04 AM - 1/1/2002, 2:13:32 AM
Location	
Report Date	9/19/2019, 4:28:39 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	8.3 mm
Mean Point Error	3.8 mm
Minimum Overlap	13.4 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
YMCA_330001	2	6.2	4.8	28.6 %
YMCA_330002	2	3.8	3.6	45.7 %
YMCA_330003	4	6.2	4.1	24.9 %
YMCA_330004	4	7.7	4.6	13.4 %
YMCA_330005	5	4.4	2.6	18.2 %
YMCA_330006	5	4.6	3.2	21.6 %
YMCA_330007	5	7.7	3.2	13.4 %
YMCA_330008	5	5.5	3.1	34.4 %
YMCA_330009	5	4.5	3.3	18.2 %
YMCA_330010	4	5.5	4.4	52.8 %
YMCA_330011	4	4.6	3.8	21.6 %
YMCA_330012	4	8.3	4.8	36.7 %
YMCA_330013	3	5.9	4.2	43.3 %
YMCA_330014	2	8.3	7.1	36.7 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
YMCA_330002	YMCA_330001	3.3	62.5 %
YMCA_330002	YMCA_330003	3.8	45.7 %
YMCA_330003	YMCA_330001	6.2	28.6 %
YMCA_330003	YMCA_330005	3.2	24.9 %
YMCA_330004	YMCA_330003	3.0	44.9 %
YMCA_330004	YMCA_330005	2.2	51.5 %
YMCA_330004	YMCA_330007	7.7	13.4 %
YMCA_330004	YMCA_330008	5.5	34.8 %
YMCA_330005	YMCA_330008	1.9	49.3 %
YMCA_330005	YMCA_330007	1.3	45.7 %
YMCA_330005	YMCA_330009	4.4	18.2 %
YMCA_330006	YMCA_330007	2.1	43.7 %
YMCA_330006	YMCA_330008	3.3	35.7 %
YMCA_330006	YMCA_330009	2.3	39.9 %
YMCA_330007	YMCA_330008	2.1	34.4 %
YMCA_330007	YMCA_330009	2.5	24.8 %
YMCA_330008	YMCA_330009	2.5	63.5 %
YMCA_330010	YMCA_330006	3.8	52.8 %
YMCA_330010	YMCA_330009	4.5	55.2 %
YMCA_330010	YMCA_330012	5.5	53.1 %
YMCA_330011	YMCA_330006	4.6	21.6 %
YMCA_330011	YMCA_330010	3.9	63.3 %
YMCA_330011	YMCA_330012	2.8	70.7 %
YMCA_330011	YMCA_330013	4.0	43.3 %
YMCA_330013	YMCA_330012	2.6	75.1 %
YMCA_330014	YMCA_330012	8.3	36.7 %
YMCA_330014	YMCA_330013	5.9	52.3 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
YMCA_330011	YMCA_330011	0.0033
YMCA_330002	YMCA_330002	0.0165
YMCA_330004	YMCA_330004	0.0111
YMCA_330014	YMCA_330014	0.0154
YMCA_330010	YMCA_330010	0.0121
YMCA_330013	YMCA_330013	0.0099
YMCA_330006	YMCA_330006	0.0193
YMCA_330003	YMCA_330003	0.0077
YMCA_330005	YMCA_330005	0.0111
YMCA_330007	YMCA_330007	0.0084
YMCA_330008	YMCA_330008	0.0125
YMCA_330001	YMCA_330001	0.0133
YMCA_330009	YMCA_330009	0.0069
YMCA_330012	YMCA_330012	0.0092

Figure A.09 - Registration Report: Y.M.C.A. Building – FARO SCENE – Focus S 350

Registration Report

Project	YMCA_350
Cluster	Scans
Recording Period	5/6/2019, 11:19:52 AM - 5/6/2019, 1:23:29 PM
Location	
Report Date	9/19/2019, 4:29:57 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	13.3 mm
Mean Point Error	6.3 mm
Minimum Overlap	10.3 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
Scan_031	4	9.5	7.1	35.3 %
Scan_032	3	6.5	5.0	35.9 %
Scan_033	2	7.9	6.4	35.3 %
Scan_018	3	8.5	5.8	10.3 %
Scan_021	2	4.4	4.2	43.4 %
Scan_022	3	7.7	5.7	11.5 %
Scan_023	4	11.2	8.5	10.3 %
Scan_024	4	11.2	6.4	11.5 %
Scan_025	5	8.3	4.7	12.3 %
Scan_026	5	13.3	6.4	18.8 %
Scan_027	5	7.9	6.2	31.5 %
Scan_028	4	9.5	4.9	22.9 %
Scan_029	5	9.5	6.5	32.2 %
Scan_030	5	13.3	8.9	18.8 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
Scan_031	Scan_032	3.8	69.8 %
Scan_031	Scan_029	9.5	42.5 %
Scan_031	Scan_030	7.2	50.4 %
Scan_031	Scan_033	7.9	35.3 %
Scan_032	Scan_033	4.9	49.3 %
Scan_032	Scan_030	6.5	35.9 %
Scan_018	Scan_022	5.1	25.8 %
Scan_021	Scan_018	3.9	55.8 %
Scan_021	Scan_022	4.4	43.4 %
Scan_023	Scan_018	8.5	10.3 %
Scan_023	Scan_024	11.2	32.2 %
Scan_023	Scan_025	8.3	12.3 %
Scan_024	Scan_022	7.7	11.5 %
Scan_024	Scan_025	2.2	50.1 %
Scan_025	Scan_026	2.5	48.3 %
Scan_026	Scan_029	5.6	40.4 %
Scan_026	Scan_030	13.3	18.8 %
Scan_027	Scan_023	5.8	32.0 %
Scan_027	Scan_024	4.5	32.8 %
Scan_027	Scan_025	6.4	36.6 %
Scan_027	Scan_026	7.9	31.5 %
Scan_027	Scan_029	6.3	32.2 %
Scan_028	Scan_025	4.0	22.9 %
Scan_028	Scan_026	3.0	36.8 %
Scan_028	Scan_029	3.1	51.9 %
Scan_028	Scan_030	9.5	25.5 %
Scan_029	Scan_030	8.3	57.3 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
Scan_021	Scan_021	0.0089
Scan_027	Scan_027	0.0594
Scan_031	Scan_031	0.0492
Scan_023	Scan_023	0.1808
Scan_024	Scan_024	0.0391
Scan_028	Scan_028	0.0028
Scan_032	Scan_032	0.0641
Scan_018	Scan_018	0.0204
Scan_025	Scan_025	0.0107
Scan_033	Scan_033	0.0689
Scan_022	Scan_022	0.0045
Scan_026	Scan_026	0.0192
Scan_029	Scan_029	0.0192
Scan_030	Scan_030	0.0598

APPENDIX B

Combined Registration Reports

Figure B.01 - Registration Report: Cushing Memorial Library – FARO SCENE – Alignment of all laser scanners

Registration Report

Project	CushingAlignment
Cluster	Scans
Recording Period	
Location	
Report Date	9/29/2019, 7:46:51 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	3.6 mm
Mean Point Error	3.0 mm
Minimum Overlap	95.1 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
Cushing_Focus330	1	2.4	2.4	98.7 %
Cushing_Focus350	1	3.6	3.6	95.1 %
Cushing_Focus3D	2	3.6	3.0	95.1 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
Cushing_Focus350	Cushing_Focus3D	3.6	95.1 %
Cushing_Focus3D	Cushing_Focus330	2.4	98.7 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
Cushing_Focus350	Cushing_Focus350	-
Cushing_Focus3D	Cushing_Focus3D	-
Cushing_Focus330	Cushing_Focus330	-

Figure B.02 - Registration Report: Animal Husbandry Pavilion – FARO SCENE – Alignment of all laser scanners

Registration Report

Project	PavilionAlignment
Cluster	Scans
Recording Period	
Location	
Report Date	9/29/2019, 7:46:21 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	3.3 mm
Mean Point Error	3.2 mm
Minimum Overlap	95.8 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
Pavilion_Focus3D	1	3.1	3.1	95.8 %
Pavilion_Focus330	2	3.3	3.2	95.8 %
Pavilion_Focus350	1	3.3	3.3	97.3 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
Pavilion_Focus3D	Pavilion_Focus330	3.1	95.8 %
Pavilion_Focus350	Pavilion_Focus330	3.3	97.3 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
Pavilion_Focus350	Pavilion_Focus350	-
Pavilion_Focus3D	Pavilion_Focus3D	-
Pavilion_Focus330	Pavilion_Focus330	-

Figure B.03 - Registration Report: Y.M.C.A. Building – FARO SCENE – Alignment of all laser scanners

Registration Report

Project	YMCAAlignment
Cluster	Scans
Recording Period	
Location	
Report Date	9/29/2019, 7:45:22 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %

Overview

Scan Point Statistics

Maximum Point Error	2.9 mm
Mean Point Error	2.4 mm
Minimum Overlap	97.1 %

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
YMCA_Focus3D	2	2.9	2.6	97.1 %
YMCA_Focus330	2	2.9	2.5	97.1 %
YMCA_Focus350	2	2.3	2.2	97.7 %

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
YMCA_Focus330	YMCA_Focus3D	2.9	97.1 %
YMCA_Focus350	YMCA_Focus3D	2.3	97.7 %
YMCA_Focus350	YMCA_Focus330	2.0	99.3 %

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
YMCA_Focus350	YMCA_Focus350	-
YMCA_Focus330	YMCA_Focus330	-
YMCA_Focus3D	YMCA_Focus3D	-

APPENDIX C

Cushing Memorial Library Measurement Locations

Figure C.01 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the northwest façade features of the Cushing Memorial Library. Data shown was collected by the Focus3D laser scanning system.

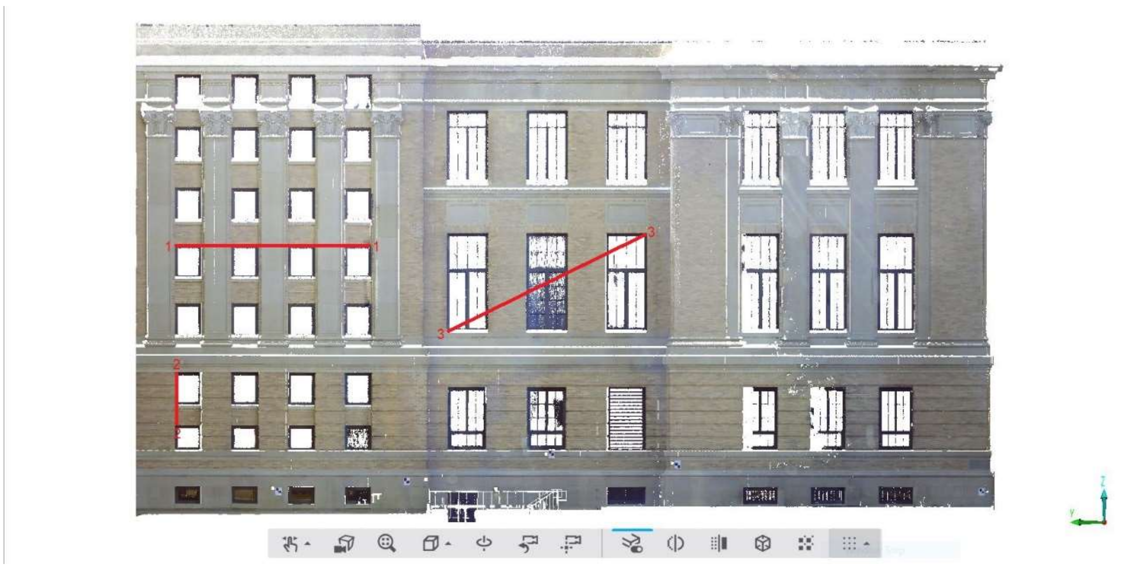


Figure C.02 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the southwest façade features of the Cushing Memorial Library. Data shown was collected by the Focus3D x330 HDR laser scanning system.

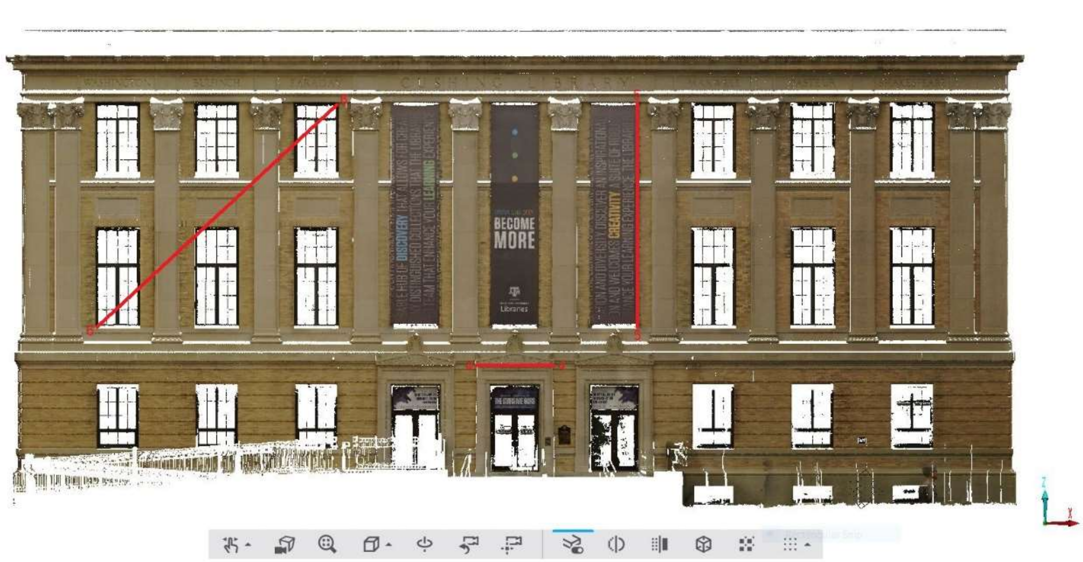
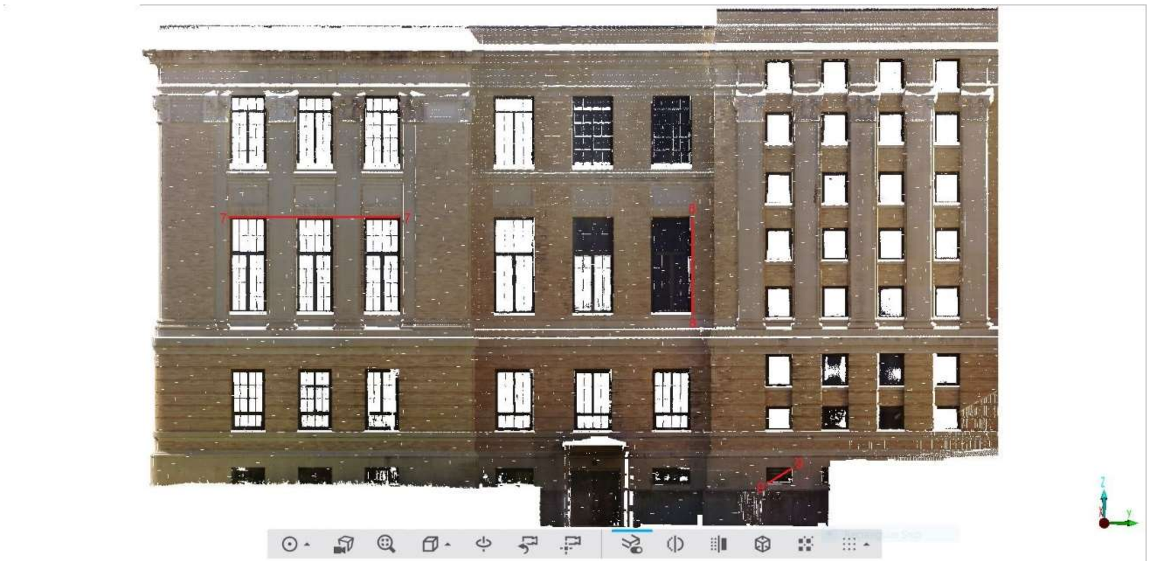
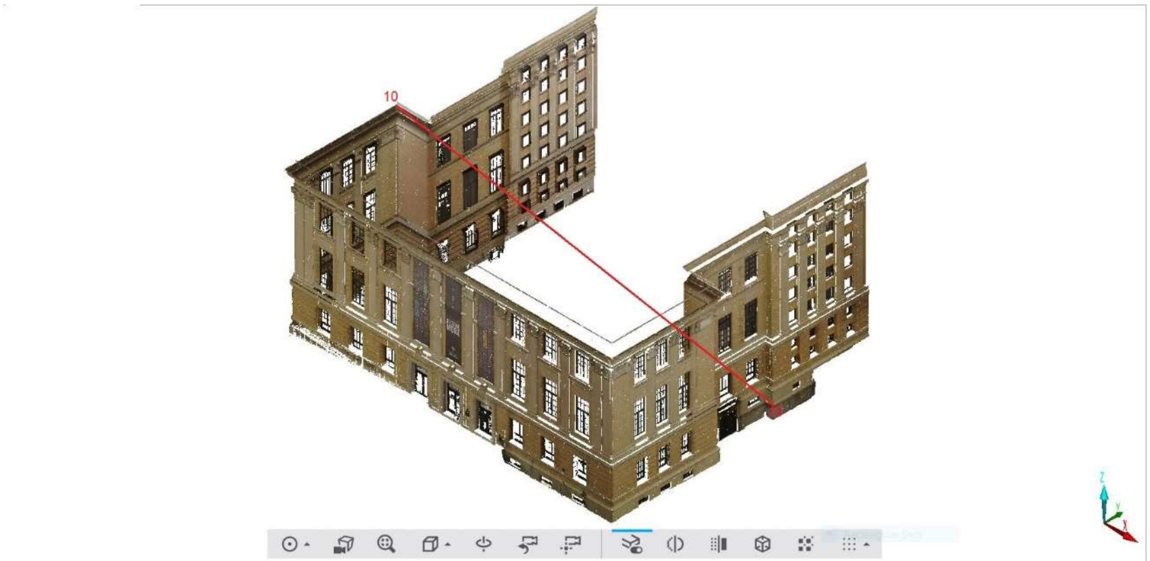


Figure C.03 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the southeast façade features of the Cushing Memorial Library. Data shown was collected by the Focus S 350 laser scanning system.



FigureC.04 - Isometric view of the volumetric measurement location between the northwest and southeast façade features of the Cushing Memorial Library. Data shown was collected by the Focus3D x330 HDR laser scanning system.



Animal Husbandry Pavilion Measurement Locations

Figure C.05 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the northeast façade features of the Animal Husbandry Pavilion. Data shown was collected by the Focus3D laser scanning system.

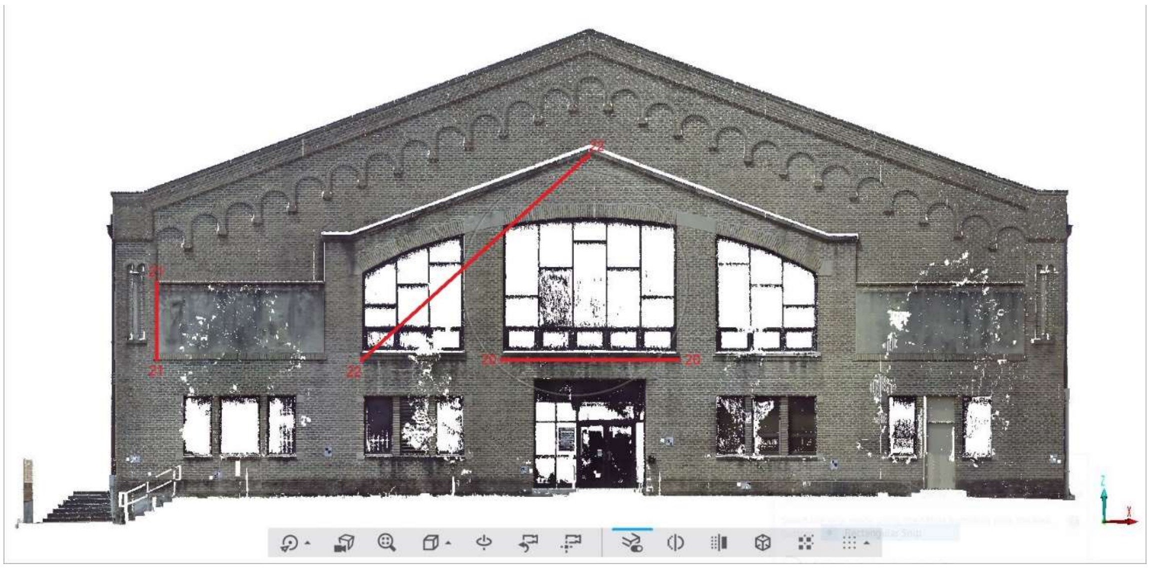


Figure C.06 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the southeast façade features of the Animal Husbandry Pavilion. Data shown was collected by the Focus3D laser scanning system.

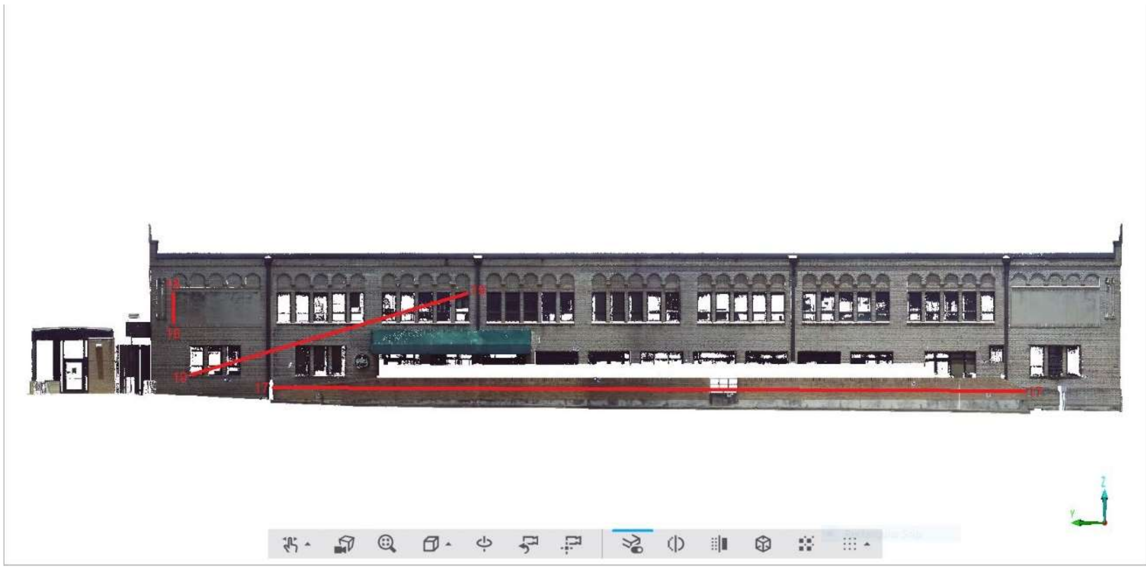


Figure C.07 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the southwest façade features of the Animal Husbandry Pavilion. Data shown was collected by the Focus3D x330 HDR laser scanning system.

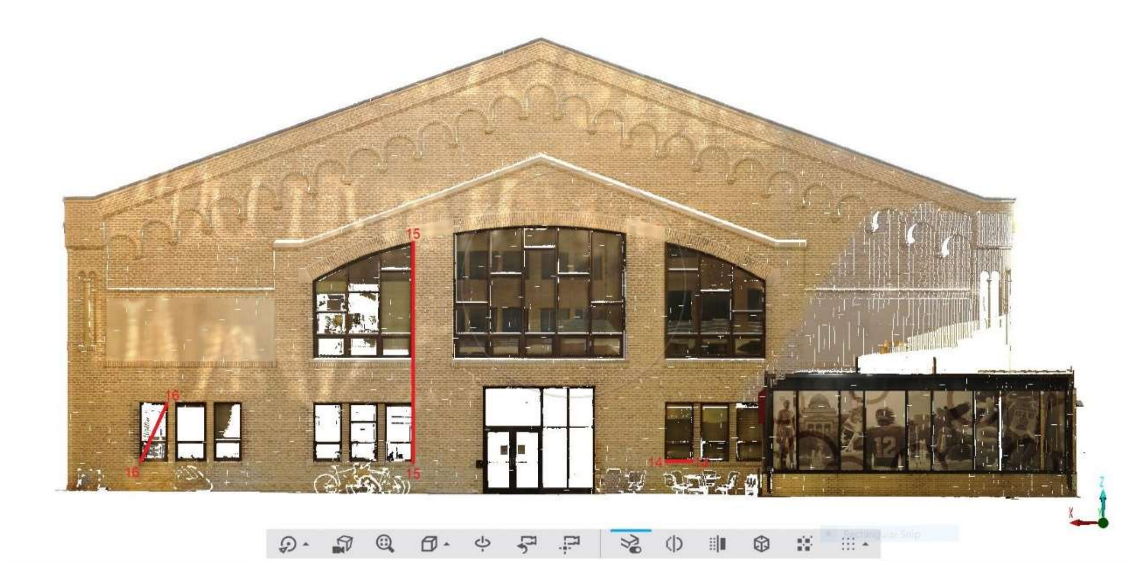


Figure C.08 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the northwest façade features of the Animal Husbandry Pavilion. Data shown was collected by the Focus S 350 laser scanning system.

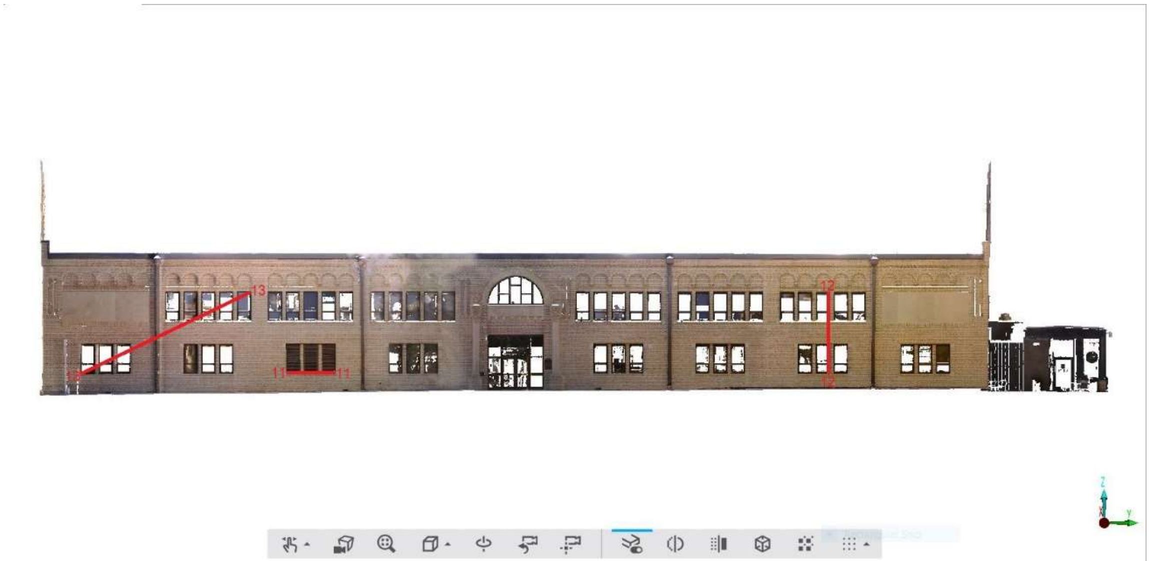
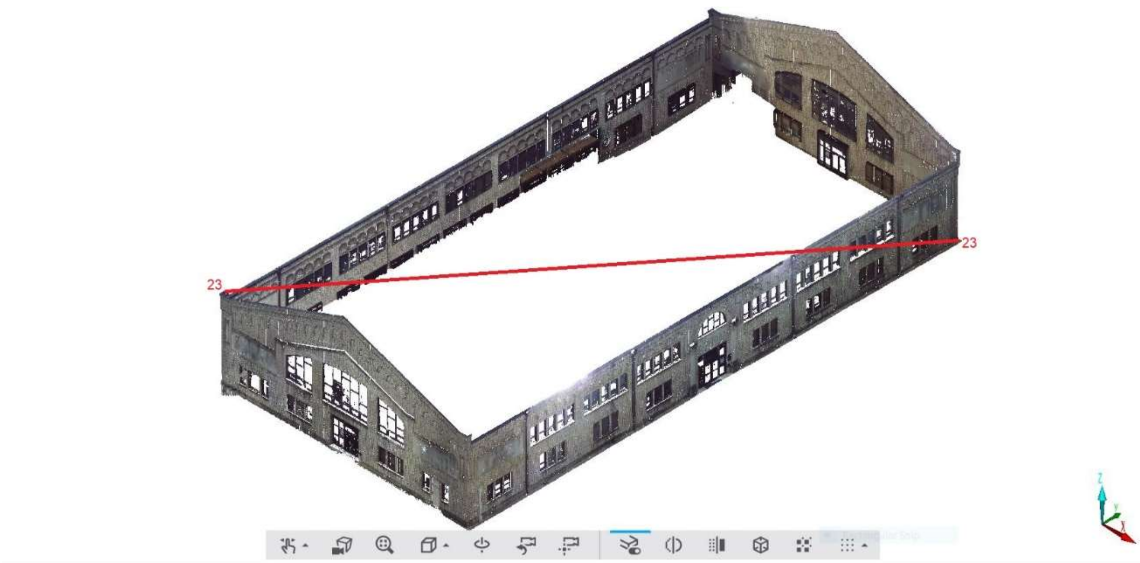


Figure C.09 - Isometric view of the volumetric measurement location between the northwest and southeast façade features of the Animal Husbandry Pavilion. Data shown was collected by the Focus3D laser scanning system.



Y.M.C.A. Building Measurement Locations

Figure C.10 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the northwest façade features of the Y.M.C.A. building. Data shown was collected by the Focus3D x330 HDR laser scanning system.

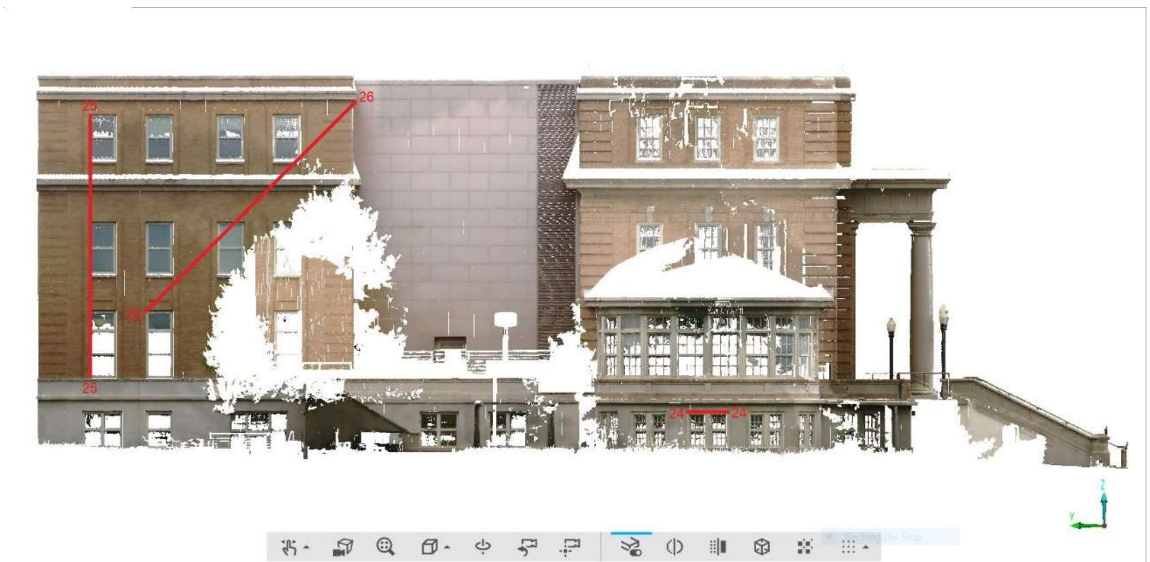


Figure C.11 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the southwest façade features of the Y.M.C.A. Building. Data shown was collected by the Focus3D laser scanning system.

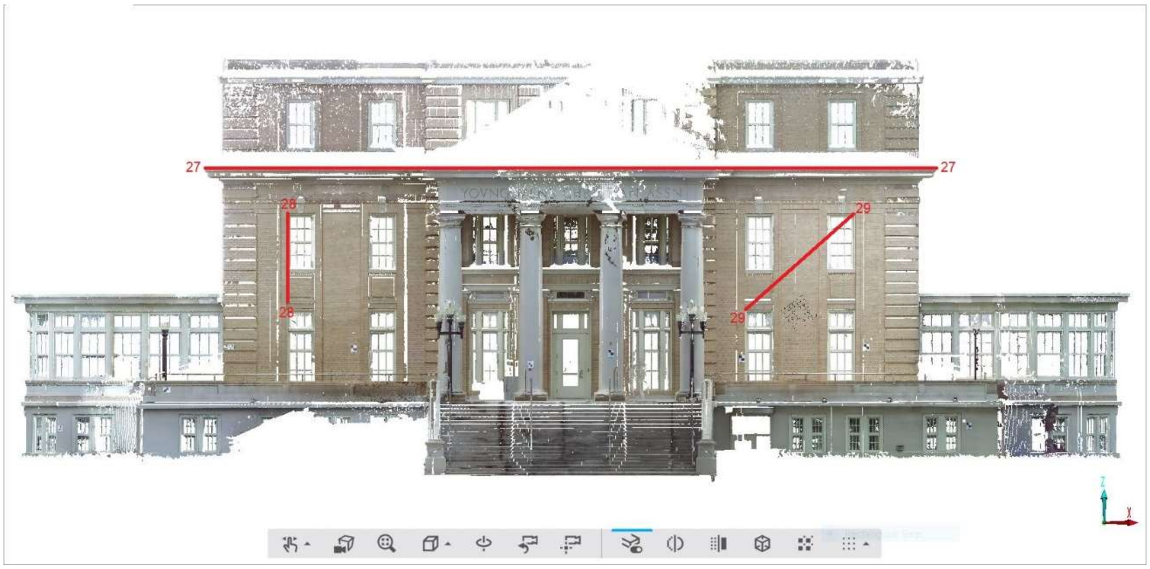


Figure C.12 - Orthographic view of the horizontal, vertical, and diagonal measurement locations on the southeast façade features of the Y.M.C.A. Building. Data shown was collected by the Focus S 350 laser scanning system.

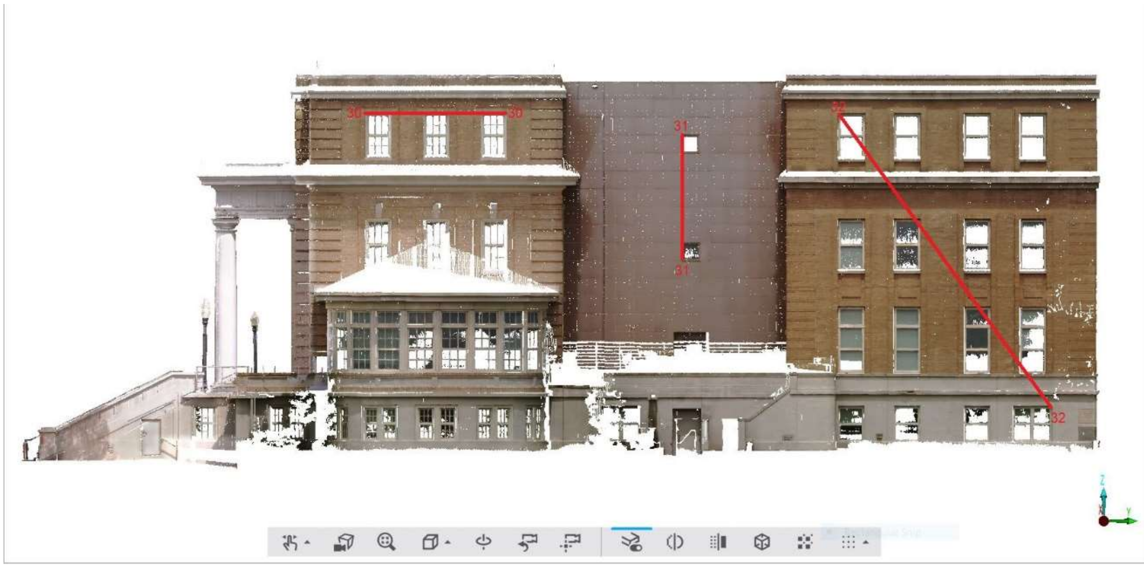


Figure C.13 - Isometric view of the volumetric measurement location between the northwest and southeast façade features of Y.M.C.A. Building. Data shown was collected by the Focus S 350 laser scanning system.