BEST PRACTICES FOR THREE-DIMENSIONAL LASER SCANNING OF CULTURAL HERITAGE

By

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To my family and friends

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IIIA	American laser classification similar to class 3R in Europe
3D	Three-dimensional
3R	European laser classification similar to class IIIA in the United States
4D	Four-dimensional
ACSM	American Congress on Surveying and Mapping
ALM	Archives, libraries and museums
APT	Association for Preservation Technology International
ASTM	American Society for Testing and Materials
CAD	Computer-aided design
CD-R	Compact disk – recordable
CH	Cultural Heritage
CW	Continuous Wave
DSLR	Digital Single Lens Reflex
E57	File format for 3D imaging data exchange
GIS	Geographic information system
GPS	Global positioning system
HABS	Historic American Building Survey
HAER	Historic American Engineering Record
HALS	Historic American Landscape Survey
HTML	Hyper text markup language
ICOMOS	International Council On Monuments and Sites
JPEG	Joint Photographic Experts Group (development group for compressed 24 bit color image storage format; also a file extension)

LIDAR	Light detection and ranging
MB	Megabyte
MM	Millimeter
MW	Milliwatt
NGO	Non-governmental organization
NRC	National Research Council of Canada
RGB	Red, green, blue
TIFF	Tagged image file format
TOF	Time of flight
UNESCO	United Nations Educational, Scientific and Cultural Organization
VR	Virtual Reality
VRML	Virtual reality mark-up language

Abstract of Thesis Presented to the Graduate School
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Technologic advances in digital imagery offer many advantages to document historic buildings and places more rapidly, accurately, and with greater ease. One such technology gaining rapid use and acceptance is the three-dimensional (3D) laser scanner. The adaptation and adoption of this technology for cultural heritage documentation is informed by the other existing uses. Best practices must be established to ensure that when using 3D laser scanning for documenting cultural heritage, the site is documented accurately and efficiently.

To establish these guidelines and protocols, existing practices must be observed, as well as new practices created. The first step is to comprehend the formalized existing best practices set forth by organizations such as English Heritage, CyArk, and Historic American Building Survey (HABS). Then, using a methodology created from the combined practices, as well as the efforts of researchers published works, 3D laser scanning documentation practices can be assessed. However because the practices have to be applicable to any site, three case studies will be used to focus on how these proposed best practices may differ in documenting sites from the recent past compared

to sites from the early 19th century. This difference in design, age, and material of the structures means that the best practices have to be broad enough to be applicable to any site.

CHAPTER 1
INTRODUCTION

Thesis Statement

Since the emergence of early man, there has been the innate need to document our existence upon the planet. Initially taking the form of early cave art that depicted, among other things, outlines of the hands of early humans, the documentation process has progressed immeasurably.[1] Evolving from these cave paintings into oral histories, into the written words of myths and fables, down the line to more accurate and precise means of documentation that includes measured drawings and photographs. In the United States, formalization of heritage documentation occurred in 1933 when the Historic American Buildings Survey (HABS) was established “to create a public archive of America’s architectural heritage, consisting of measured drawings, historical reports, and large-format” black and white photographs.[2]

The process of documentation of the physical environment and heritage has now entered the digital age. While the current technologies are by no means the ultimate form of documentation, they currently provide aspects of documentation that were once unfathomable. One such current method of documentation is the use of three-dimensional (3D) laser scanning technology.

The modern day laser scanner captures millions of distinct points from environments or objects without physically touching them by using one of two

[1] Ker Than, "World's Oldest Cave Art Found—Made by Neanderthals?" National Geographic. National Geographic Society, last modified June 14, 2012, http://news.nationalgeographic.com/news/2012/06/120614-neanderthal-cave-paintings-spain-science-pike/ (accessed 8 July 2013).

[2] United States Department of the Interior, National Park Service. *Historic American Buildings Survey: Guidelines for Historical Report.* (Washington, D.C.: U.S. United States Government Printing Office, 2007), 1.

measuring methods: time-of-flight or phase-shift measurement technologies.[3] These methods for measuring the distances of objects and environments differ between scanners, and in some respects provide different results. However, the measurement methods are not the only differences between scanners. With numerous companies manufacturing scanners, each with its own proprietary software and hardware, there emerges distinct varieties of laser scanning documentation techniques. This is because with each new generation of scanner, the capabilities of the scanner increase. Companies such as Faro, Leica, and Trimble produce scanners that have different features that aid in the documentation process.

One aspect that remains congruent, despite the hardware and software differences, is that when "capturing high resolution three-dimensional images of complex environments and geometries, large-volume 3D laser scanners provide a fast, efficient way to capture millions of data points for use in comprehensive 3D models or detailed reconstructions."[4] The application of three dimensional laser scanning to document heritage sites is still in its infancy. The planning, scanning, and processing of 3D laser recording varies greatly. A set of guidelines need to be established to ensure that, despite the type of scanner used, or method of measurement collection, the product remains the same. Currently the creation of best practices for digital documentation of heritage sites using a 3D laser scanner is ongoing. Because practices may vary based on the type of site being documented or the type of laser

[3] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

[4] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

scanner being used to document, there can only be a flexible framework of guidelines to ensure that proper documentation occurs.

Motivation

The reason for why there needs to be a set of standards or guidelines for the documentation of heritage sites with a laser scanner may not be readily apparent to an amateur without the understanding of the types of standards that existed for older documentation techniques for cultural heritage purposes. "Traditional methods for capturing complex 3D environments include steel tape measures, piano wire, plumb bobs, laser range finders and total stations."[5] These methods often required specialized training and a rigid set of standards to ensure that the built environment was documented to the best of the documenter's abilities. However, with these methods there exist downsides to the documentation process. "These traditional methods of collecting data can be extremely user intensive, time consuming, and can result in inconsistencies in measurement across different users."[6] Large sites would often require teams to document them, whereas with a laser scanner, the documentation team can be reduced to a few individuals. Additionally, team members may record information differently, leaving discrepancies in measurements that could result in an inaccurate representation of the site.

"The process of documenting a complex 3D environment using traditional methods can take days, weeks, or even months, and at the end of this process perhaps only thousands of measurements have been collected, which is a relatively small

[5] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901
[6] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

number to thoroughly document an environment."[7] Considering that some projects can in fact take a team of a dozen individuals weeks to document a streetscape, the same streetscape can be documented with a team of two in a matter of hours with a laser scanner. The processing of the scans may take longer than the actual acquisition of scan points, but the total combined man-hours is still much less than that of traditional methods.

Although "traditional methods are slow, time-consuming and present a number of evident limitations", these methods provide individuals with the documentation knowledge and understanding that are required as a foundation for the establishment of best practices in newer forms of documentation.[8] Only by hand measuring a building using a datum line and plumb bob does the documenter get a tactile feel for the building and its construction. This aspect may be lacking if the documenter processing the scans had not visited the site, and was relying on field notes and second hand information from those who were documenting the site with a 3D laser scanner. Robert Warden, Professor of Architecture at Texas A&M University, feels that "turning back the clock for students by teaching hand-documentation techniques is a valuable pedagogical exercise" but continues with the argument that "requirements of professional practice often necessitate efficient merging of staff talent with available

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[7] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

[8] Hung-Ming Cheng, Ya-Ning Yen, Min-Bin Chen, and Wun-Bin Yang, "A Processing for Digitizing Historical Architecture." In *Digital Heritage Third International Conference, EuroMed 2010, Lemessos, Cyprus, November 8-13, 2010 : Proceedings*, edited by EuroMed 2010 (2010 : Limassol, Cyprus) and Marinos Ioannides. (Berlin: Springer, 2010), 1.

tools" to ensure that documentation efforts continue to be as efficient and comprehensible as possible.[9]

Agreeably, traditional methods should in no way be thrown aside for these newer technologies. These technologies however do offer users the ability to create intricate 3D models that can be visited repeatedly by the user, models that can focus on significant surfaces or areas of a structure and be captured accurately and quickly.[10] The digital model of the site would allow the user to continuously reference the original site when needing to take new measurements or double check any hand measurements. These digital models would of course have to be more accurate than traditional hand drawings, and they have proven to ensure precision. "For example, in a typical 360° scan of an indoor scene, investigators can collect 10 million points in about 5 minutes – capturing details at the scene down to the millimeter."[11] With this level of accuracy, the produced models are ensured to be usable by multiple industries that all have different standards and tolerances for their measurement requirements.

The framework for the production of guidelines or standards is set forth in the technology itself. Because it is able to produce this level of accuracy, it is a baseline from which all the further requirements can be produced. Collaboration between fields that use this technology is required to establish what the possibilities and capabilities are for 3D laser scanning. Again within these fields, there needs to be a common framework that can be agreed upon that encompasses all scanner technologies, all site

[9] Robert Warden, "Towards a New Era of Cultural-Heritage Recording and Documentation." *APT Bulletin* 40 (3/4): (2009), 7.

[10] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

[11] FARO. *Laser Scanning for Forensic Investigations*. 18 May 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1679

types, and all final products of the documentation. The UNESCO Charter on the Preservation of Digital Heritage established that “preservation of the digital heritage requires sustained efforts on the part of governments, creators, publishers, relevant industries and heritage institutions.”[12] In the United States HABS has therefore made an effort to assess the pros and cons of using laser scanning to document cultural heritage. Only through the collaboration of all of these parties can a consensus be achieved in order to ensure that the digital heritage is not restricted to proprietary software programs and files. These factors contribute to the digital divide, the inequality between groups to have access to or use of the digital heritage products. The charter goes on to state that “in the face of the current digital divide, it is necessary to reinforce international cooperation and solidarity to enable all countries to ensure creation, dissemination, preservation and continued accessibility of their digital heritage.”[13] To achieve this grand idea, the initial step is the creation of standards and guidelines for 3Dlaser scanning for heritage purposes.

Goals

Before a set of guidelines can be developed it must be understood what the final product of the documentation will be. A set of guidelines for the documentation of the complete works of Shakespeare is different from that of the documentation of how the Space Race influenced American architecture. For heritage purposes, “the ideal documentation of an object would allow the user to gain the same complete information

[12] UNESCO Charter, "The UNESCO Charter on the Preservation of the Digital Heritage." (2003).

[13] Ibid.

as an investigator who examines the original on site."[14] Ideally, a complete and accurate facsimile of an object or site is required to ensure that experiences remain the same. However, it is important to note that there can never be any true facsimile of a site, because it would not encompass all of the sense and experiences of the user. After all, a facsimile site cannot occupy the same exact point in space and time as the original.

Three-dimensional models representing the as-built conditions of a site are a perfect way to achieve the goal of ideal documentation. Often times sites are at risk in one way or another, be it human created or natural threats, and thus 3D laser scanning, as a form of documentation is necessary. In fact, "capturing 3D as-built documentation of fragile, historic structures with laser scanners allows archaeologists and researchers to gather necessary measurements with a non-contact device – reducing the risk for further deterioration, and pinpointing areas for restoration and conservation."[15] Moreover, documentation in its purest form is conservation, by documenting a site or structure, a record is created of the existence of the structure, safeguarding the imbued history and knowledge of the site should anything happen to the original. If this should happen, the record has to be as detailed as possible to ensure that any reconstruction or restoration work done is as true to the original form as possible.

To ensure that documentation is done in a way that ensures high accuracy of details and recording of elements of importance, standards were agreed upon. In fact,

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[14] Wolfgang Bohler, "Comparison of 3D Laser Scanning and Other 3D Measurement Techniques." In *Recording, Modeling and Visualization of Cultural Heritage*, edited by Emmanuel P. Baltsavias: (Taylor & Francis Group, 2006),89 .

[15] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

the Venice Charter adopted by ICOMOS in 1965 states that “it is essential that the principles guiding the preservation and restoration of ancient buildings should be agreed and be laid down on an international basis, with each country being responsible for applying the plan within the framework of its own culture and traditions.”[16] Despite the charter being written nearly fifty years ago, the principles established by it continue to shape current preservation efforts. Those committee members who drafted the charter were able to see that every effort must be made to ensure the accurate safeguarding of monuments and sites. Their foresight is evident in Article 2 of that charter that states, “The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage.”[17] What is not written is that these sciences and techniques must have an existing set of standards or practices that can be adopted or adapted to encompass the goals of heritage conservation Without these standards, the preservation through documentation could create erroneous data. Therefore, to avoid these issues, an understanding of the current uses and their possible values for heritage preservation must be achieved. Once this is accomplished, then standards and best practices can be extruded from the current accepted practices in other fields.

Uses for Scanning

The fields in which lasers are used as accurate measuring devices are much diversified, almost as diverse as the objects being measured. Early laser scanning was comprised mainly of aerial LIDAR, or Light Detection and Ranging. In fact, the

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[16] Venice Charter, "International Charter for the Conservation and Restoration of Monuments and Sites." (1964).

[17] Ibid.

“technology had been in use by various industries since the 1970s, but by 1997 the technology was transformed for terrestrial uses and had already been employed in heritage projects.”[18] While many scanners were originally constructed for purposes outside of cultural heritage, they have become accepted as an efficient documentation method for cultural heritage. At the same time, some agencies designed scanners that were made entirely for the purposes of cultural heritage documentation. For example, the NRC, or National Research Council of Canada, started developing their own 3D laser scanner in 1981.[19] Whether the digitization by way of 3D laser scanning was for cultural heritage purposes or not, there exist procedures or guidelines that include but are not limited to “economic management and the logistic activities which take place in the offices, but also on-stage artistic production and craft-made activities in workshops.”[20]

Engineering

One of the original uses for a 3D laser scanner was for industrial purposes. Large plants were documented with laser scanners so that a precise 3D model could be created. Within this model, the users could then bring in Computer Aided Design (CAD) files of objects that were to be installed into the real world environment. Often times

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[18] Robert Warden, "Towards a New Era of Cultural-Heritage Recording and Documentation." *APT Bulletin* 40 (3/4): (2009), 7.

[19] J. Taylor, J-Angelo Beraldin, Guy Godin, R. Baribeau, L. Cournoyer, P. Boulanger, F. Blais, Michel Picard, M. Rioux, and J. Domey, "Culture as a Driving Force for Research and Technology Development: A Decade's Experience of Canada's NRC 3D Technology." In *Digital Applications for Cultural and Heritage Institutions*, edited by Vito Cappellini, Electronic Imaging and the Visual Arts Conference, James Hemsley and Gerd Stanke. Aldershot, Hants, (England : Burlington, VT: Ashgate, 2005).

[20] Hung-Ming Cheng, Ya-Ning Yen, Min-Bin Chen, and Wun-Bin Yang, "A Processing for Digitizing Historical Architecture." In *Digital Heritage Third International Conference, EuroMed 2010, Lemessos, Cyprus, November 8-13, 2010 : Proceedings*, edited by EuroMed 2010 (2010 : Limassol, Cyprus) and Marinos Ioannides. (Berlin: Springer, 2010), 9.

these objects can be pipes or large pieces of machinery that are being inserted to make the plant more efficient. The precision achieved with 3D laser scanning and creation of objects saves on time and costs, all the while reducing the chances of having to do onsite field modifications on the new objects.

Survey

The act of surveying already has its own set of standards that call for accuracy of points that 3D laser scanning can provide. This required accuracy of points is in the definition:

> Surveying, as defined by the American Congress on Surveying and Mapping (ACSM), is the science and art of making all essential measurements to determine the relative position of points or physical and cultural details above, on, or beneath the surface of the Earth, and to depict them in a usable form, or to establish the position of points or details.[21]

The definition also calls for some form of visualization, which can be achieved with a point cloud model created from the 3D scans. With the use of a 3D laser scanner, millions of points are collected with each scan ensuring that the entirety of a site is surveyed down to the millimeter level.

Accident

Three-dimensional laser scanners are used in accident reconstruction; they scan the environment of the accident and collect all of the evidence in the scans. From these scans a model is produced, and is then analyzed by the "application of physics principles" to determine what the cause of the accident was.[22] The reason why this field

[21] FARO. *Surveying Basics*. 16 August 2012. Available from: FARO: http://www2.faro.com/site/resources/details/492

[22] FARO. Tilo Voitel and Toby Terpstra, Kineticorp, LLC. *Benefits of 3D Laser Scanning in Vehicle Accident Reconstruction*. 8 May 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1769

adopted 3D laser scanning is that it enables the entire environment to be captured at once, giving the user the ability to access the scans, and determine any measurement from them. That way, “regardless of which measurements are required later in the reconstruction, a detailed laser scan will ensure that the 3D point data necessary for these measurements is available.”[23]

Forensic

Similar to accident reconstruction is the field of crime scene investigation. Because the protocols of crime scene investigation are so strict, to ensure no damage to evidence, noncontact measuring devices are beneficial. “At a typical crime scene, investigators, technicians and other law enforcement officers must decide which parts of the scene are relevant to their case; what to photograph, what to measure, and what to collect.”[24] However, as stated above, a 3D laser scanner can be used to document the scene in its entirety. If the scanner has a built in camera, then it also is able to take photographs of the scene. Often however, very high definition photographs are required for objects that are possibly vital evidence. Though there arises the question of which the possible hundreds or thousands of items at a crime scene are relevant to the crime, meaning that if the scene was documented with traditional methods, it could take days to catalog everything.[25]

[23] FARO. Tilo Voitel and Toby Terpstra, Kineticorp, LLC. *Benefits of 3D Laser Scanning in Vehicle Accident Reconstruction*. 8 May 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1769

[24] FARO. *Laser Scanning for Forensic Investigations*. 18 May 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1679

[25] FARO. *Laser Scanning for Forensic Investigations*. 18 May 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1679

Cultural Heritage

Some preservationists approach historic sites with deductive reasoning skills akin to fictional detective Sherlock Holmes. Each site is analogous to a crime scene, where the perpetrator is often the elements and the passage of time. The same procedures that allow crime scene investigators to produce tooth contour replicas from chewed gum at a crime scene can be used to determine what tools left specific patterns on the materials scanned on a heritage site.[26] Accuracy, portability, and the ability to capture true colors of objects are all requirements when documenting for cultural heritage purposes, the very same requirements that are assessed for new universal technologies.[27]

Three-dimensional laser scanning is still in the early adoption phase in regards to historic preservation. The reasoning behind this is because most of the documentation work is done using other forms of documentation, "including hand measuring, digital photogrammetry, surveying with total stations, long-range airborne light, distance and ranging (LIDAR) scanning, and global positioning systems (GPS)."[28] Therefore, the full capabilities and limitations of using a laser scanner to document cultural heritage sites are still not fully understood. Each site, product, and technology will present its own difficulties and hurdles the scanning team will have to overcome. That is why a set of

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[26] Jennifer Birkenstamm, Janusz Godyn, Francesca Khani, Evita Sadamin, and Richard Siderits, "Three-Dimensional Laser Scanning of Crime Scene Gum as a Forensic Method Demonstrating the Creation of Virtual Tooth Surface Contour and Web-Based Rapid Model Fabrication." 04; 2013/8. (2010), . http://go.galegroup.com/ps/i.do?id=GALE%7CA233044467&v=2.1&u=gain40375&it=r&p=AONE&sw=w. (accessed 25 Sept. 2013).

[27] Marco Callieri, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Processing Sampled 3D Data: Reconstruction and Visualization Technologies." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (2011).

[28] Karen E. Hughes and Elizabeth I. Louden, "Bridging the Gap: Using 3-D Laser Scanning in Historic-Building Documentation." *APT Bulletin* 36 (2/3), (2005), 38.

general standards must be established, so that they are broad enough to encompass all scenarios. "Although the expectations and deliverables differ greatly between the disciplines, the processes developed for engineering projects formed the foundation for laser-scanner use" for cultural heritage preservation and documentation.[29] From this foundation, a set of best practice considerations can be established to ensure that all heritage sites scanned with a 3D laser scanner are done so efficiently and accurately to produce the proper deliverables needed for the preservation of the site.

[29] Ibid. 45.

CHAPTER 2
LITERATURE REVIEW

Guidelines and Practices

The protocols established for the best practices of 3D laser scanning are treated the same way as the pirate code. Captain Barbossa explains it best by stating, “The code is more what you’d call ‘guidelines’ than actual rules.”[1] The fact is that the practices are fluid and ever changing, evolving as the technology and uses develop over time. Practices differ amongst countries and countries, as well as institutions and organizations, but there is one guideline agreed upon by all, that the use of 3D laser scanner should always be done in conjunction with other documentation techniques.

International

While analyzing readings and case studies on laser scanning being used internationally, “it was made obvious that there exists no established universal documentation methodology for cultural heritage assets, but instead great variations in the systems of collecting and organizing data from buildings in the European countries.”[2] However, there does exist some attempts to establish methodologies for 3D laser scanning that have been attempted to bridge the methods between countries.

Kioussi et al. feel that “in order for any new methodology for monument documentation to be effective and widely applicable, not only it needs to be harmonized with existing European standards but also, most importantly, be able to cater for the

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[1] Pirates of the Caribbean: Curse of the Black Pearl, Film, Directed by Gore Verbinski, (Burbank: Walt Disney Home Entertainment; 2003).

[2] Anastasia Kioussi, Maria Karoglou, Asterios Bakolas, and Antonia Moropoulou, "Integrated Documentation Protocols Enabling Decision Making in Cultural Heritage Protection." In *Progress in Cultural Heritage Preservation*, 211-220: (Springer, 2012), 212.

variety and the particularity of cultural heritage, applying the best possible organization and management of knowledge."[3] Therefore, for these protocols to be integrated, experts from documentation organizations around the world need to come together to establish best practices that transcend country specific regulations.

English Heritage produced a document that gives advice and guidance on laser scanning heritage sites in 2006, as well as a revised document in 2011. The goal of the publication was:

> to provide, to English Heritage employees and other professionals engaged in cultural heritage, general news and independent information about all forms of 3D survey and recording, in-depth guidance and discussion on specific applications and techniques, and to provide access to a network of relevant organisations and individuals that could provide information and advice.[4]

In addition, while this publication featured case studies that were mainly within the United Kingdom, it was written in such a way to encompass general principles that could be applied or adapted depending on the country documenting the heritage site.

One of the first points of advice English Heritage suggests is a factor common during the site assessment phase of a 3D documentation project. This key factor "in commissioning a survey is being aware of what point density and measurement accuracy is required to generate the level of deliverable data required by the project."[5] English Heritage conveniently provides a chart, depicted in Figure 2-1, that shows what

[3] Ibid. 213.

[4] English Heritage. *3D Laser Scanning for Heritage (second edition): Advice and guidance to users on laser scanning in archaeology and architecture.* Edited and brought to press by David M. Jones. Swindon, (UK: English Heritage Publishing, 2011), 3.

[5] Ibid. 10.

point densities are recommended for different sized projects.[6] It is then up to the project staff to determine the capabilities of the scanner to ensure that the correct distances from the object can be achieved to accurately record the site at these densities.

Although not expressly stated in the sections on commissioning a survey or data processing, English Heritage does eventually tackle the issue of why a scanner may be the preferred form of documentation in the case studies. One of the main reasons a scanner may be used is because of the ease and speed with which it is able to capture points. This is especially helpful for sites that contain many unusual shapes or forms. For example, a laser scanning group who documented the Byzantine Crypt of Santa Cristina stated that “irregularly shaded walls covered with a number of fairly well preserved frescoes made us decide to model the inside with a laser scanner.”[7]

A large section of the guidelines provided focus on the way in which the 3D point cloud data is managed. This data management phase includes data processing and analysis. The laser scanning professionals at English Heritage found that “while a meshed model might be required, plans, profiles, sections and elevations (line drawings) could be generated by using the point cloud as a base from which features are traced, based on the edges in the geometry and intensity data.”[8] All of these products would have been determined at the initial project planning assessment phase.

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[6] Ibid. 10

[7] J-Angelo Beraldin, Michel Picard, Sabry F. El-Hakim, Guy Godin, Virginia Valzano, and Adriana Bandiera, "Combining 3D Technologies for Cultural Heritage Interpretation and Entertainment." International Society for Optics and Photonics (2005).

[8] English Heritage. *3D Laser Scanning for Heritage (second edition): Advice and guidance to users on laser scanning in archaeology and architecture.* Edited and brought to press by David M. Jones. Swindon, (UK: English Heritage Publishing, 2011), 13.

They argue that analysis is the main reason for collecting 3D point cloud data on a site. A recommendation they put forward is that supplementary data should always be used in analyzing the site, which can occur either during or after the product creation.[9] One of the reasons why they prefer analysis of a site with a laser scanner is because the scanner produces 3D data, which allows for queries in 3D as well. One way that this can be accomplished is through "line-of-sight analysis," which "allows a user to quantify if one part of the model can be seen from another location."[10]

As each site is different, and each project has different goals, there is no set standards on what type of products can be produced from the 3D point clouds. Because a laser is able to pick up minor differentiations that are not perceptible to the naked eye, it is an invaluable tool in the field. This minute "information can be useful, in some cases, in differentiating between slight changes in surface or material type," this may help in better understanding a site.[11] Other products that can be used to produce a site are 3D digital models. One scanning group used the laser scan data from multiple sources to digitally repatriate artifacts. "To illustrate the concept of 'digital repatriation', a 3D model of a replica of Tutankhamun's funeral mask was integrated into the 3D model of the tomb."[12] Another example of digital repatriation occurred when scans were completed of the Gavet Collection housed in the Ringling Museum of Art in Florida, and digitally placed back into a model created from scan data of the Gothic Room of Marble

[9] Ibid. 14.

[10] Ibid. 14.

[11] Ibid. 14.

[12] J. Taylor, J-Angelo Beraldin, Guy Godin, R. Baribeau, L. Cournoyer, P. Boulanger, F. Blais, Michel Picard, M. Rioux, and J. Domey, "Culture as a Driving Force for Research and Technology Development: A Decade's Experience of Canada's NRC 3D Technology." In *Digital Applications for Cultural and Heritage Institutions*, edited by Vito Cappellini, Electronic Imaging and the Visual Arts Conference, James Hemsley and Gerd Stanke. Aldershot, Hants, (England : Burlington, VT: Ashgate, 2005), 31.

House in Newport.[13] The laser scanning group CyArk, whose standards are mentioned later in this chapter, completed this project.

Another topic of interest among many parties is the issue of data archiving. The reason why data archiving is important is that with any new technology or form of documentation, the lifetime of the documentation has to be established. English Heritage suggests, "If you want to ensure that data can be used in the future, it is recommended that service providers should retain the proprietary observations after completion of the survey for a minimum of six years."[14] This type of practice is best described as short-term data archiving, and includes many materials needed for the ensured reusability of the data. These materials include "field notes and/or diagrams generated while on site; the raw and processed data used for the final computation of co-ordinate and level values; and a working digital copy of the metric survey data that form each survey."[15] These materials must all be saved in file formats that have longevity and can be read by multiple programs to ensure continued viability. Some of the following recommended formats can represent the types of raw and interpreted scan data:

- digital terrain models (DTM): any text based grid format
- triangular irregular network (TIN) models: Wavefront OBJ
- CAD drawings: DXF, DWG
- movies/animations: QuickTime MOV, Windows AVI
- rendered images: TIFF, JPG

[13] Scott Lee, "Digital Repatriation: Marble House." CyArk. CyArk, last modified June 3rd, 2011, http://archive.cyark.org/digital-repatriation-marble-house-blog. (accessed 6 July 2013).

[14] English Heritage. *3D Laser Scanning for Heritage (second edition): Advice and guidance to users on laser scanning in archaeology and architecture.* Edited and brought to press by David M. Jones. Swindon, (UK: English Heritage Publishing, 2011), 15.

[15] Ibid. 15.

- replication: STL[16]

With these formats, it is easier to ensure that these born digital files will have a slightly longer lifespan.

CyArk

Digitally preserving cultural heritage sites from around the world, CyArk is a non-profit organization whose mission accomplishes this “through collecting, archiving, and providing open access to data created by laser scanning, digital modeling, and other state-of-the-art technologies.”[17] By working with technology partners in countries across the globe, CyArk has the unique advantage of being able to combine methodologies into a singular methodology that meets their selective documentation criteria. This means that the main way CyArk’s digital preservation methodology distinguishes itself “from other methods is that these digital tools are used in a way that allows them to be easily integrated.”[18]

CyArk produced a draft document of project standards and procedures, with which laser scanning teams can correctly and accurately document heritage sites. This “document is meant to serve as a living document that will continue to grow as technologies and methods are updated and research is expanded.”[19] Currently the document covers standards and procedures for documentation planning, surveying,

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[16] Ibid. 15

[17] CyArk. *Draft - The CyArk 500 Project Standards and Procedures.* (Orinda, CA: CyArk, 2009), 4.

[18] Ibid. 4.

[19] Ibid. 4

high definition survey using a terrestrial 3D laser scanner, photography, capturing panoramic and composite images, and metadata.

During the site assessment phase, CyArk recommends a documentation plan that is efficient in capturing the resource by reducing the number of setup locations needed to document the site without losing important point data. The reason behind this recommendation is that “efficiency in the field is crucial to the quality of the scan data that is returned, the battery life of the scanner, and risk of damage to the scanner.”[20] Additionally, no matter the range of the scanner, CyArk suggests distances that the scanner cannot exceed from the subject/site and the reference targets. CyArk recommends, “Although subjects may be at distances up to 100m, it is best practice to restrict the distance from the scanner to targets to at least half that distance.”[21]

Similar to the English Heritage recommendations, CyArk also has some rules regarding resolution or point cloud density for its documentation projects. Some of the required standards are as follows:

- Point density should be equal in vertical and horizontal spacing
- Point density will vary over distance and irregular surfaces, and therefore the chosen point density should be the best-possible, or maximum, point density obtained.
- Point density is affected by the angle-of-incidence from the scanner to the subject. Oblique angles can distort the spot size of the laser, affecting the overall accuracy of the point cloud.[22]

Similar to English Heritage’s standards for large stone masonry subjects, CyArk requires a 5mm minimum point density for scan subjects. [23] Additionally, CyArk requires

[20] Ibid. 11

[21] Ibid. 11

[22] Ibid. 12

a 50mm minimum point density for “contextual information such as topographic features surrounding a scan subject,” similar to English Heritage’s required density for small earth works.[24]

Additionally CyArk has standards set for the placement of targets, which is an important step of the site assessment phase. According to their standards, four targets are required to be surveyed for each scan location, although additional targets can be used for registration without the need of being surveyed. Identical to recommendations found in the user manuals accompanying scanners, CyArk requires a minimum of three targets overlapping between any two scans for registration purposes.[25]

While some scanners contain built-in cameras, CyArk recommends the use of an external Digital SLR (DSLR) camera. This camera is “required to capture High Dynamic Range Panoramic Images via multi-frame, bracketed photos” which in turn are used “to provide photo-realistic 3D renderings of the captured 3D point cloud data.”[26] These pictures are best taken in the top down approach, where the camera is removed from the tripod to take the last picture of the ground where the tripod stood.

HABS, HAER, HALS

In the United States, there are three documentation programs created by the federal government to record heritage structures and sites, these programs being the Historic American Buildings Survey (HABS), Historic American Engineering Record (HAER) and the Historic American Landscapes Survey (HALS). The HABS, HAER, and

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[23] Ibid. 12

[24] Ibid. 12

[25] Ibid. 13

[26] Ibid. 13

HALS “programs are tasked with creating guidelines and standards for the documentation of America’s architectural, engineering, and landscape heritage through the production of measured drawings, large-format photographs and written histories.”[27] These items make up the collections, the goal of which is to provide scholars, engineers, architects, and interested members of the public with the documentation materials of sites and structures “significant in American history and the growth and development of the built environment.”[28]

The additional benefit of these programs is that the repository of knowledge acts as the last means of preservation for some buildings. This is because “when a property is to be demolished, its documentation provides future researchers access to valuable information that otherwise would be lost.”[29] HABS/HAER/HALS programs recognize that 3D digital documentation has a place in the recording of historic resource, but feel that that place is one of supplementation at the moment.

National Park Service experts have come to the consensus that “while laser scanning is gaining momentum in the field of heritage recording, scans are only the tip of the iceberg when it comes to creating comprehensive documentation that is useful in efforts such as rehabilitation and historical investigation.”[30] Although the standards set

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[27] United States Department of the Interior, National Park Service. *Producing HABS/HAER/HALS Measure Drawings from Laser scans: the Pros and Cons of Using Laser Scanning for Heritage Documentation.* By Catherine Lavoie and Dana Lockett. (Washington, D.C.: U.S. United States Government Printing Office), 1.

[28] United States Department of the Interior, National Park Service. *HABS/HAER Standards.* (Washington, D.C.: U.S. United States Government Printing Office, 1990).

[29] Ibid.

[30] United States Department of the Interior, National Park Service. *Producing HABS/HAER/HALS Measure Drawings from Laser scans: the Pros and Cons of Using Laser Scanning for Heritage Documentation.* By Catherine Lavoie and Dana Lockett. (Washington, D.C.: U.S. United States Government Printing Office), 1.

forth for laser scanning by these programs are not as detailed as the ones previously analyzed above, there are some similarities. For example, these programs require that the 3D laser scans be supplemented with hand-measuring, so that after the scans have been processed, complete with point cloud mitigation techniques, the scans can be brought into AutoCAD and other programs “to produce two- (and sometimes three-) dimensional drawings to its standards.”[31]

The data submitted for these programs is done so in mostly a visual manner. While text is often submitted, the main submissions for documentation include large format back and white photographs, as well as filed sketches and measured drawings. Measured drawings are preferred over laser scans because measured drawings are more easily understandable, and they are known to have long-term permanence, which scans do not.[32] The reason behind this is that records created digitally form the beginning, are not known to have long lifespans. This is because file formats change, and programs that read the files can quickly become obsolete. Luckily with the help of the Library of Congress, these file formats are being explored “in order to mitigate the significant back-end costs involved in the storage and frequent upgrading of files.”[33] However, for now the requirement for documentation remains to be hard copy products, until the time comes when this is no longer an issue.

As with the CyArk and English Heritage, the issue of long-term archiving and data storage is a significant hurtle that must be handled. The Secretary of the Interior’s Standards and Guidelines for Architectural and Engineering Documentation requires

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[31] Ibid. 1.

[32] Ibid. 2.

[33] Ibid. 2

that the documentation must be "reproducible and durable long-term, and that it is clearly and concisely produced."[34] Specifically, it is Standard II, which states that the documentation should be prepared accurately from reliable sources and that the limitations of the documentation should be clearly stated so as to permit independent verification of the information recorded.[35]

Archival quality documentation requires a set of standards that are still being established. However, HABS/HAER/HALS all rely on previously established archive standards to inform their decisions. They feel that "in establishing archives, the important questions of durability and reproducibility should be considered in relation to the purposes of the collection."[36] The preferred durability of a record for these programs is a material that can last 500 years. Color photography does not meet this standard; however, it is believed that ink on mylar (plastic paper) does. Additionally these programs allow for field records, despite them not meeting the archival standards, because these records aid the collection users in understanding the site/structure that was documented.[37]

Since the purpose of the documentation is the preservation of a historic property through an accurate recordation, "the documentation must include information that permits assessment of its reliability."[38] Additionally, for the archival products to be useful, it is recommended that the files be produced on "durable materials that are able

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[34] Ibid. 2

[35] United States Department of the Interior, National Park Service. *HABS/HAER Standards.* (Washington, D.C.: U.S. United States Government Printing Office, 1990).

[36] Ibid.

[37] Ibid.

[38] Ibid.

to withstand handling and reproduction, and in sizes that can be stored and reproduced without damage."[39] Despite this, the 3D laser scan point clouds are recommended to be copied onto a compact disc (CD) and included with the field notes.[40] The file type that the 3D laser scan is saved as is not specified, which might lead to problems in the future. Furthermore, CDs are known to have a relatively short archival life, but since the laser scan data is only considered supplemental, this is not an urgent issue.

The HABS/HAER/HALS programs have some flexibility in their standards, much like the standards of CyArk and English Heritage. One example is how they allow for multiple types of media to be used in the documentation process, "such as films of industrial processes," however they advise that if these materials are used, the respective "office should be contacted before recording."[41]

Despite the open-mindedness in the variety of documentation methods shown by these programs, HABS/HAER/HALS remain interested in traditional techniques. For example on of the reasons "the programs combine recording methods is that laser scanning does not engage the recorder in the same manner that hand-measuring does."[42] They feel that these traditional practices instill an understanding of the site and its construction process.

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[39] Ibid.

[40] United States Department of the Interior, National Park Service. *HABS Guidelines: Recording Historic Structures and Sites with HABS Measured Drawings.* (Washington, D.C.: U.S. United States Government Printing Office, 2008).

[41] United States Department of the Interior, National Park Service. *HABS/HAER Standards.* (Washington, D.C.: U.S. United States Government Printing Office, 1990).

[42] United States Department of the Interior, National Park Service. *Producing HABS/HAER/HALS Measure Drawings from Laser scans: the Pros and Cons of Using Laser Scanning for Heritage Documentation.* By Catherine Lavoie and Dana Lockett. (Washington, D.C.: U.S. United States Government Printing Office), 3.

General

While these standards and guidelines carry the most weight when adopted by these larger organizations and institutions, more apropos guidelines can be generated by those working closely with the technology in the field. While these guidelines may sometimes be project specific, they often are broad enough to be applicable to any 3D documentation effort.

One example of this is a recommendation from a scanning team trying to save time and money by being efficient in the scanning process. The team recommended three steps for making the scanning process more efficient:

- Determine overall base scanning accuracy for the building.
- Precisely identify areas of interest for higher accuracy scanning.
- Provide guidance on how to and who will use the direct deliverables from the scanning.[43]

By following these three steps in the project planning assessment phase and site assessment phase, they were able to mitigate the possibilities of having gathered too much scan data for what kind of projects were to be produced. This reduction continues from these phases into the data management phases when the multiple scans would have been registered together to make the project point cloud.

Another example of best practices in efficiency can arise on a project that has "repetitive elements, such as roof tiles, dormer sections, and other ornamental trim."[44] Documenting these items would add higher costs to a project, and could have little value for the documentation process. Since a repetitive element ideally could be

[43] Caroline R. Alderson, Beth L. Savage, Charles Matta, Calvin Kam, and Anne E. Weber, "Government Policy and Practice: Digital Conservation and Landscape Renewal." *APT Bulletin* 41 (4): (2010), 14.

[44] Ibid. 14.

documented once, and then just replicated, rather than individually documenting each individual element. However, if the product calls for that kind of documentation, then this streamlining of the process cannot be done. However, if they are not needed to be documented, than these elements could be "consequently released from the high-accuracy requirement so that repeating elements not having direct impact on the project objectives could be copied and inserted into design documents, rather than modeled to show actual conditions."[45]

Another guideline for efficiency arises when traversing from the data gathering phase to the data management phase of the 3D laser scanning pipeline. A scanning team found that "in post-processing, the project benefitted by involving managers of the modeling team in the field scanning in order to capture field knowledge and reduce ambiguity in interpreting building features from the laser-scan point-cloud data."[46] This small step cuts down on the number of hours spent producing deliverables, as well as the number of hours spent determining the importance of features that the processing team knew nothing about.

Integration with Other Documentation Techniques

As mentioned multiple times, as with any form of documentation, 3D laser scanning should and can be supplemented with other forms of documentation. One technique, which is often used as a comparative analysis to 3D laser scanning, is the process of photogrammetry to document a site. Often times, the result of using this process can produce cleaner lines than those developed from a point cloud model.

[45] Ibid. 14

[46] Ibid. 14

There are many cases, however, where one process is better than the other. For example, one project included the documentation of a stone wall. The team found that "a 3D model of the stone wall" contained "far more information than a line drawing" and conveyed the shape of the wall in three-dimensions much better.[47] Within a comparable time frame, the 3D scans produced far clearer and more informative results than the photogrammetric techniques.

There are in fact instances where the photogrammetric process produces results that are far more accurate. During the data management phase, line drawings can be created from the 3D point cloud in a program such as AutoCAD. During this process, the 3D model is rotated around, while lines are drawn along the edges of the model, snapping to points along the path. However, "this procedure is very time-consuming, because the point cloud has to be rotated permanently to get a 3D impression and to be able to snap the correct points (e.g. on edges)." [48] Whereas this process would, result in lines that could possibly deviate from their correct positions, due mostly to the point densities of the scan, a photogrammetric process could result in more correct and precise line drawings.

Photogrammetry also has the added ability of being used in many of the same instances as 3D laser scanning. Both laser scanning and photogrammetry can be done airborne as well as terrestrially. There are some downsides to photogrammetry being used in the air however. This is because "as a non-active measurement technique (photographs only record the light reflected from the sun or other illumination source) it

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[47] W. Boehler and A. Marbs, "3D Scanning and Photogrammetry for Heritage Recording: A Comparison." (2004).

[48] Ibid.

is less able to measure through small gaps" such as in those found in forest canopies.[49] Whereas with the use of a laser scanner, if the resolution was high enough, a larger point density would be able to pick up these small gaps in the forest canopy.

Synopsis

While it may seem that the best practices being promoted by these organizations are varied in their approach, they are fostered by the common goal of accurate and efficient documentation of a heritage site, the data of which should stand the test of time. Where English Heritage emphasizes the data management phase, CyArk emphasizes the data gathering phase, and HABS/HAER/HALS emphasize the data archiving phase. The publications provide details on the other phases of the 3D laser scanning pipeline, for example HABS/HAER/HALS weighs the pros and cons of 3D laser scanning as part of the site and technology assessment phases. However, each program's main function clearly affects how much emphasis is made into researching the best practices of specific phases despite covering all phases of the pipeline. Additionally, as the one clear goal of the multiple practices remains the same, each program insists that 3D laser scanning be a tool that is one of many used for the complete and accurate documentation of a heritage site.

[49] English Heritage. *3D Laser Scanning for Heritage (second edition): Advice and guidance to users on laser scanning in archaeology and architecture.* Edited and brought to press by David M. Jones. Swindon, (UK: English Heritage Publishing, 2011), 17.

Table 2-1. Appropriate point densities (sampling resolutions) for various sizes of cultural heritage feature

feature size	example feature	point density required to give 66% probability that the feature will be visible	point density required to give a 95% probability that the feature will be visible
10m	large earth work	3500mm	500mm
1m	small earth work/ditch	350mm	50mm
100mm	large stone masonry	35mm	5mm
10mm	flint galleting/large tool marks	3.5mm	0.5mm
1mm	weathered masonry	0.35mm	0.05mm

Contents as found in English Heritage’s 3D Laser Scanning for Heritage: Advice and guidance to users on laser scanning in archaeology and architecture (pg. 10).

CHAPTER 3
METHODOLOGIES

Despite the fact that contemporary documentation processes have changed considerably from earlier, more traditional methods, the goals of heritage documentation have changed little over time. These goals include “conservation of design and construction knowledge, conservation of material and aesthetic heritage, promulgation of cultural awareness.”[1] While the goals may remain the same, the methods with which they are achieved need to be standardized to ensure that correct documentation occurs. In the case of 3D laser scanning for heritage purposes, many institutions, companies, individuals, and advisory councils have been considering the establishment of best practices or guidelines, as noted in chapter two. The Director of the Center of Preservation Research at the University of Colorado Denver, Ekaterini Vlahos, has suggested that the practices be broken down into categories that are part of the 3D laser scanning pipeline. She breaks the pipeline down into six categories, with smaller sections of guidelines and protocols that should be followed within each:

- Project Planning Assessment: developing project goals, desired data management planning, and technology assessment.
- Site Assessment: data capture planning, site scale assessment, site conditions, accessibility, context, and environmental conditions.
- Technology Assessment: cost, time, and accuracy requirements.
- Data Gathering: acquisition techniques, emerging technologies, accuracy, and completeness.
- Data Management: processing of digital data, application, representation, and accessibility.

[1] Robert Warden, "Towards a New Era of Cultural-Heritage Recording and Documentation." *APT Bulletin* 40 (3/4): (2009), 7.

- Data Archiving: short and long term data storage, metadata backups, file formats, and accessibility.[2]

These categorical breakdowns enable the protocols to be used to ensure that proper documentation can occur no matter the site or technology used. These can apply to terrestrial time of flight laser scanners, terrestrial phase shift scanners, or even aerial LIDAR scanners. Using this basic framework set forth by Ekaterini Vlahos in combination with research from other documentation experts, the following standards were created.

Planning Assessment

Project Goals

One of the first steps with any project is to establish the primary project goal and objectives and what the deliverables are going to be. Once the goal, objectives, and deliverables are established, then the framework can be laid out to ensure proper completion. In cultural heritage, assessing whether the goal is to purely document the site, documenting for the sake of future work, or documentation for the purposes of interpretation, all require different strategies. For example, “virtual restoration can be used to improve the understanding of a site (legibility of textual and pictorial information) without turning to interventions often traumatic for the original copy.”[3] To achieve this goal the entire site or just selective elements can be documented using the 3D laser scanner. After processing the data, restoration techniques can be virtually applied to

[2] Ekaterini Vlahos, "Best Practices for Digital Documentation." Abstract. *3D Digital Documentation Summit*. (2012).

[3] J-Angelo Beraldin, Michel Picard, Sabry F. El-Hakim, Guy Godin, Virginia Valzano, and Adriana Bandiera, "Combining 3D Technologies for Cultural Heritage Interpretation and Entertainment." International Society for Optics and Photonics (2005),1 .

the site using other programs or software. This means that the plan eventually has to call for an additive interpretation to the data collected with the 3D laser scanner.

While with other cultural heritage projects, the goal can be just the opposite. The main goal of a project may be to document an entire site, only to then subtract elements out of the model. "Elements that were added in a site over the years can be removed and the digital 3D model of that site can then be viewed in the correct historical context," so that without harming the existing structure, it can be visualized as it stood in any era as long as the traces remained to be documented in the present.[4]

Technology Assessment

Three-dimensional laser scanning technology can be used to acquire digital information of sites or relics in many ways. There are two different types of measurement techniques, which use different technologies. For example, 3D documentation can be done "using a robot arm to make a measurement (contact measurement), or applying optical principals to make a measurement (non-contact measurement)."[5] These factors need to be taken into account during the planning phase, because the site or relic may be too fragile for a contact measurement device, resulting in the need for a non-contact measurement device. Whether the historic building or heritage resources and sites require a contact or noncontact device will depend on the assessed fragility of the site.

"In most of the practical applications, the generation of digital 3D models of heritage objects or sites for documentation and conservation purposes requires a

[4] Ibid. 1.

[5] Dongming Lu and Yunhe Pan, *Digital Preservation for Heritages Technologies and Applications*. (Heidelberg ; New York : Hangzhou: Springer ; Zhejiang University Press, 2010), 12.

technique or a methodology" that is accurate, portable, comes at a low cost, is capable of fast acquisition, and flexible.[6] A 3D laser scanner may be required to scan sites that are at the cultural landscape scale, or on the other side of the spectrum on the object/ornamentation scale. Assessing the technology needed for the documentation, requires a more in depth analysis, which is why it is examined in greater detail later in the 3D laser scanning pipeline.

Site Assessment

Data Capture Planning

Usually sites that are going to be documented with a 3D laser scanner have been previously documented in one form or another. It is helpful to collect these original forms of documentation, and use them as the foundation for data capture planning. Some examples of existing documentation are existing Historic American Building Survey. Drawings, copies of original blueprints or construction documents, even satellite images of a site captured through Google Maps can be useful in the data capture planning stage. However, it is important to note, that nothing ever is constructed according to plan, and many of these records may be obsolete in one fashion or another. For example, an image taken from a satellite for Google Maps may show the structure surrounded by small trees, while in reality the image is a few years old, and the vegetation could be overgrown throughout the site.

Using existing drawings, or hand sketches made on site, the laser scanning team then marks out where the scanner needs to be positioned at the site to collect the

[6] Fabio Remondino, "Accurate and Detailed Image-Based 3D Documentation of Large Sites and Complex Objects." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks, F.Stanco, S.Battiato and G.Gallo, Eds.,* (*Boca Raton*: 2011),129.

information that is needed. Additionally, if the site requires more than one scan, which is usually the case, then additional locations of the scanner and placement of reference targets also needs to be planned. “The use of reference targets or objects in the scan environment can be used to tie together multiple scans, each on their own coordinate system onto a single, aligned coordinate system.”[7] Since the scanner works on a line of site system, meaning it only catches points that it is able to see, the scanner will have to be moved around the site to capture every detail. This means that in order to ensure that scan can be registered to one another it is best to have at least three reference targets that overlap in each scan. This will aid in the registration process by ensuring that scans and scanning locations can be triangulated to one another.

Scans of interior spaces are easier to register to each other than scans of exterior spaces, necessitating a more diligent approach to the placement of exterior targets. Luckily, “for those objects to be scanned in a well-controlled environment (for example: indoor space and no obstruction problem), objects can be oriented” so that they can be scanned completely without registration targets.[8]

Site Scale Assessment

As mentioned above, the scale of the site is important to take into account during the planning phase. Different 3D laser scanning systems may be needed depending on the relative size of the site compared to the time available to scan it and the capabilities of the scanner. If the site is large, and there is little time, then a scanner with a greater

[7] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

[8] Hung-Ming Cheng, Ya-Ning Yen, Min-Bin Chen, and Wun-Bin Yang, "A Processing for Digitizing Historical Architecture." In *Digital Heritage Third International Conference, EuroMed 2010, Lemessos, Cyprus, November 8-13, 2010 : Proceedings*, edited by EuroMed 2010 (2010 : Limassol, Cyprus) and Marinos Ioannides. (Berlin: Springer, 2010), 3.

range will be needed, whereas if there were little time constraints a scanner with smaller range can be used multiple times within the site to document everything. An advantage to 3D laser scanning technology is the very wide working volume many of the scanners can achieve, being able to “scan an entire building façade or a city square with a single shot.”[9]

Site Conditions

Existing conditions are exactly what the 3D laser scanner is going to document when used on a site. However, sometimes the existing conditions do not lend themselves well to the act of scanning. For example, documentation may be required of a structure that is covered in vines or other forms of vegetation. Since the scanner collects only the points it is able to see, the exact wall will not be documented, rather the vegetation obscuring the wall will be documented. It is also important to assess the condition of the site in regards to safety. Those who are documenting the site with the 3D laser scanner may be putting themselves and the equipment in danger if they need to step onto rusted platforms to ensure that all facets of a site are documented.

Accessibility

Safety is also a concern when it comes to public accessibility. Many times a site will be documented with a 3D laser scanner while occupied or accessed by others. Because the scanner uses a laser beam to record measurements, there is inherent danger to individuals on the site. The laser beam used by the scanner can be harmful to laser operators depending on what strength the laser is classified. Therefore, team

[9] Marco Callieri, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Processing Sampled 3D Data: Reconstruction and Visualization Technologies." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (2011) 3:,71.

members should ensure that proper precautions are taken to guarantee that the public is not exposed to the laser or come to any harm from the scanning process. Accessibility also refers to the ability to navigate the entire site for an accurate and complete documentation using the 3D laser scanner. Equipment, such as a boom lift, may be needed to access the roof of a structure, if there is no built in access point. Additionally there may be locations on a site that may not be scanned because a high enough vantage point cannot be achieved, thus resulting in an incomplete 3D point cloud.

Context

The context of the site is also important to take into account when doing the site analysis. There may be elements around the site that can adversely affect the 3D documentation process. For example, a site that is to be documented may be situated on a river, or some other body of water. Unless this body of water has frozen over, this greatly reduces the amount of locations on which the laser scanner can be placed to document the site (except if the team has a mobile scanner that can be attached to a boat). Additionally, if the site is in an urban context or a rural context, this makes a difference. The scanning team will be more likely to have to deal with passersby, traffic, and other variables in the urban context than if they were in the rural context. These factors all need to be taken into account during the site setup and planning phases.

Environmental Conditions

Planning and assessing environmental conditions is sometimes difficult. In the plan, it is ideal to set aside a few extra days if an exterior is being scanned in the event of inclement weather. Some plans that allow for scanning of both interior and exterior spaces can allow the scanning team to plan for scanning exteriors when the weather is better suited, and then use the remaining days for the interior. Another difficulty that will be elaborated on in the technology assessment section is the existence of fog or smoke.[10] The small particles in the air may catch the laser beam before it hits the portions of the site being documented, and thus hinder the scanning process. It is also important to note the ambient temperatures of the site. Most 3D laser scanners, like most electronic equipment, function best when not exposed to extreme temperatures. Additionally, since the laser is just a form of light, bright lights or sunlight can result in the laser not registering any points, because the beam is lost in the stronger light source. As of yet "there is no single approach that works for all types of environment and at the same time is fully automated and satisfies the requirements of every application."[11]

Technology Assessment

When measuring the distance between an object and a laser, many different methods can be used. "All of them take advantage of three basic attributes of laser light: unobscured light travels in straight lines; the velocity of light when travelling in space is known; the light produced by a laser is typically only a single wavelength light and is thus easy to detect."[12] These fundamental principles of lasers allow for the creation of 3D laser scanners that differ in numerous ways in regards to how the laser captures measurement data.

[10] Elli Angelopoulou and John R. Wright Jr., "Laser Scanner Technology." (1999), 18.

[11] J-Angelo Beraldin, Michel Picard, Sabry F. El-Hakim, Guy Godin, Virginia Valzano, and Adriana Bandiera, "Combining 3D Technologies for Cultural Heritage Interpretation and Entertainment." International Society for Optics and Photonics (2005).

[12] Elli Angelopoulou and John R. Wright Jr., "Laser Scanner Technology." (1999), 11.

General

To assess which type of laser is best for which project, a general understanding of basic laser principles is required. Five different phenomena can occur when a laser is used are refraction, reflection, absorption, scattering, and polarization. These behaviors are related to the materials the laser passes or attempts to pass through. Refraction occurs when only part of the laser light passes through an object, such as water, with the beam changing direction or bending. Reflection occurs when part of the laser light is reflected back from the surface. Another possibility is that of absorption; where part of the light is absorbed by the surface material and the energy is converted into other forms, such as heat. Scattering is most likely to occur when the laser light hits particles that are diffused over an area or volume, as is the case with fog or smoke, which results in the laser light getting scattered about. Polarization occurs when the vibration of the beam of light changes after hitting a surface, sometimes then only vibrating parallel to that surface. Different materials can react differently and produce different phenomena when the laser beam hits them. These produced effects often change the wavelength, the direction, the intensity, or the vibration of the laser light beam resulting in correct, incorrect, or misaligned measurement data.[13]

There are two types of reflection that can occur with a 3D laser scanner, which need to be taken into account when documenting a site. These two types of reflection are specular reflectance and diffuse reflectance, and occur depending on the material the laser light hits. "Specular, or mirror-like, reflectance is the type of light that we get reflected from a surface like glass, or polished metals, surfaces that are smooth on the

[13] Ibid. 4.

scale of the wavelength of the light."[14] When the laser light hits this type of reflection, the beam continues off in the new direction, until it hits a diffuse reflectance surface, and the combine total measurement is applied to the initial angle of the laser. This results in stray points that are not documenting the correct surface of a material. "Diffuse reflectance on the other hand is produced by matte surfaces, like a piece of paper, that are rough on the scale of the wavelength of light."[15] These types of surfaces are more likely to produce the desired measurement results with less creation of stray points in the point cloud.

Classification

All lasers are rated on one classification system or another. This is because there is an inherent amount of risk, since a laser is a form of radiation. In fact, the term laser originated as an acronym for light amplification by stimulated emission of radiation. "The health risk associated with a laser is directly related to the energy output of the laser, which in turn depends on the wavelength, the average output power in Watts, the total energy per pulse, the pulse duration and the pulse frequency."[16]

Laser classifications are usually agreed upon by one or more countries, to ensure that an understanding is achieved and that safety of individual operators is ensured. In the United States, "all lasers are classified as belonging to one of six possible categories, depending on how hazardous they are," whereas in European nations, there are seven classifications of lasers.[17] The classifications used in the

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[14] Ibid. 5

[15] Ibid. 5

[16] Ibid. 8

[17] Ibid. 8

United States are Class I, Class II, Class IIa, Class IIIa, Class IIIb, and Class IV, as seen in Table 3-1.[18] "In 2001 the standard governing the safety of laser products in Europe (EN) and Internationally (IEC), was substantially revised and the Classification system was overhauled."[19] This reclassification resulted in the following laser classes, which can be seen in Table 3-2: Class 1, Class 1M, Class 2, Class 2M, Class 3R, Class 3B, and Class 4.[20]

Cost

Assessing the cost of equipment is important for project planning. Not only is the price of the scanner important, but all other pieces of hardware and software as well. Most 3D laser scanners are relatively expensive, ranging anywhere from $60,000 to $275,000 or roughly € 50,000 and € 200,000. [21] Additional costs associated with the scanner hardware include ancillary items such as the tripod, the carrying case, the reference targets, safety goggles etc. All of these items are usually relatively expensive because they can be made specifically for that particular scanner. Additional costs are incurred with the purchase of software packages, which are usually proprietary to the scanner purchased. However, these programs may not perform all of the necessary functions, and additional software packages may need to be purchased to complete the project goals. [22] Another indirect cost is the cost of the hardware or computers to run

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[18] Ibid. 9.

[19] FARO. *Laser Classification*. 29 August 2011. Available from: FARO: http://www2.faro.com/site/resources/details/502

[20] Ibid.

[21] W. Boehler and A. Marbs, "3D Scanning and Photogrammetry for Heritage Recording: A Comparison." (2004).

[22] Ibid.

these programs, because some models and software may put a strain on the average computer operating system.

Time

Another requirement for many 3D lasers scanners used for heritage documentation is that they be efficient with their time. Time can be broken down into two major categories: the time it takes for actual data capturing, and the time it takes to set up and take down the scanner. Generally at most sites one would want a scanner that is “light weight and easy to set up”, portable enough to access hard to reach areas, and “can operate in low or even no-light environments.”[23] Although some scanners cannot meet these exact specifications, they may prove to be still useful depending on the site.

Accuracy

A 3D laser scanner is only as good as its accuracy of measurement. For terrestrial laser scanning there are two methods for capturing measurement data using the laser. These two types are named from how the measurement is calculated, either by time of flight (TOF) or by measuring the phase shift.

Three-dimensional laser scanners that measure using TOF literally measure the time of flight of a laser pulse from the 3D laser scanner to object and back again to the scanner. Three-dimensional laser scanners that use TOF “are typically used for large distances like hundreds of meters or many kilometers,” and are capable of achieving accuracies over short distances to a degree of “a few millimeters or centimeters.”[24]

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[23] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901
[24] FARO. *Phase Shift Measurement and Time of Flight Measurement*. 25 April 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1772

The basic principle behind TOF 3D laser scanners is that using the constant of the speed of light, which is known, any distance can be measured by calculating how long a round trip from the scanner to the object takes. The formula for this calculation is (c*t)/2, where t is the time it takes the laser to compete its roundtrip and c is the constant speed of light. "Clearly the accuracy of a time-of-flight 3D laser scanner depends on how precisely we can measure the time: 3.3 picoseconds (approx.) is the time taken for light to travel 1 millimeter."[25] Therefore, as the technology continues to increase in its ability to measure light, the accuracy of the measurements will increase as well.

The other option for 3D laser scanning systems is that of a scanner that uses phase shift technology. Just like TOF scanners "phase-shift systems also emit a laser light; however, in phase-shift technology, the laser is emitted at a specific frequency, and the reflection of this wavelength is 'shifted' or 'displaced' by its impact on a surface.[26] This process, diagramed out in Figure 3-1, takes place both inside and outside the scanner. To calculate the distance, "the distance is measured by analyzing the shift in the wavelength of the return beam."[27] Once the amount of displacement is known, then the distance between the scanner and the object can be precisely calculated.

Now comparatively each type of scanner has its share of advantages and disadvantages. However, "in general, phase-shift scanners are faster, more accurate,

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[25] Ibid.

[26] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

[27] FARO. *Phase Shift Measurement and Time of Flight Measurement*. 25 April 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1772

and provide higher resolution data" when compared to TOF scanners.[28] Again many users feel that when comparing scanners they notice that some of the "disadvantages of TOF devices are the lower accuracy and lower sampling density (i.e., the inter-sampling distance over the measured surface is usually in the range of a centimeter)."[29] In cultural heritage, a centimeter can contain a significant amount of data. Compare that to a phase shift scanner that is "capable of capturing points at up to 976,000 points per second with an accuracy of +/- 2mm," and a documentation team would be more than likely willing to use a phase shift scanner for projects that require great details and accuracy.[30]

Despite which scanner is chosen for the documentation effort, there are still issues that arise that cause inaccuracies in the scan data. The first of which is the encountering of "fine particles in the air, like those that compose smoke, snow, rain or fog".[31] As mentioned above, these particles cause the scattering effect, where the beam is scattered about the site, resulting in a large number of stray points. However, this may not always be the case. Because light is a wave, but acts as a beam, that is how it is generally perceived. However, since it is a wave, it may pass around an object that is smaller than the oscillation of the wave. Essentially, it is as if the particles do not

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[28] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

[29] Marco Callieri, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Processing Sampled 3D Data: Reconstruction and Visualization Technologies." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (2011) 3:,71.

[30] FARO. *Laser Scanning for Forensic Investigations*. 18 May 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1679

[31] Elli Angelopoulou and John R. Wright Jr., "Laser Scanner Technology." (1999), 18.

exist, as diagramed in Figure 3-2, and the beam continues on its trajectory to scan the site. [32]

Another reason that a 3D laser scanner may be inaccurate is if the laser beam only partially hits an object. These partial hits, are hitting two distinct points, but giving them one measurement. Laser scanning scholar Wolfgang Bohler describes it best by stating:

> When the laser beam actually hits an edge point, the recorded coordinates tend to show range deviations (phantom points, artifacts) since only part of the laser spot is reflected from the object, and they show angular deviations since the coordinates are computed for the center of the beam and not for the center of the part of the beam that really hits the object.[33]

This phenomenon, diagramed in Figure 3-3, creates points that are inaccurate, and may be out of line with other points on the object. Luckily many software programs that come with the scanner allow for the removal of stray points created in this manner, for a cleaner more accurate 3D model of the site.

Data Gathering

Acquisition Techniques

It should be again noted at this point that the steps that are being described in this thesis are being applied directly to documenting with a 3D laser scanner. Best practices for documentation in general dictate that those documenting a site do not rely only on one form of documentation. Data can be acquired about a site in many different media, with the most obvious being through hand measurement and large format photography. Other formats of 3D digital data collection all have their own strengths

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[32] Ibid.

[33] Wolfgang Bohler, "Comparison of 3D Laser Scanning and Other 3D Measurement Techniques." In *Recording, Modeling and Visualization of Cultural Heritage*, edited by Emmanuel P. Baltsavias: (Taylor & Francis Group, 2006), 91.

and weaknesses, and can be found in Table 3-3.[34] However, as this thesis is focusing on the practices required for scanners, the main emphasis is on the 3D laser scanner.

While hand measurement is a respectable means for acquiring measurement data, it often will run into problems. “Scale and irregular or organic forms are two conditions that present particularly difficult, though not impossible, problems for traditional methods of hand measurement.”[35] When selecting where the scanner will be placed in the planning phase, it is important to think about at what resolution the scanner will be documenting. The aforementioned recommended resolution table (Table 2-1) provided by English Heritage provides some basic guidelines on what resolutions will be needed for what size product.[36] It is then up to the scanning team to ensure that the scanner is set to collect measurements at that density, and the scanner is close or far enough to achieve those densities.

Primary tools, other than the 3D laser scanner, used to acquire data on the site are the targets. There are a few types of targets, the two most common being the checkerboard square and the other the matte sphere. The checkerboard square can be efficient in that it is inexpensive to make, and can be easily attached, such as taped, to most surfaces. The only downside to this two-dimensional, flat target is that if viewed at too much of an angle, it will not register during processing as a target. The sphere on the other hand has an advantage when it comes to angles. No matter which angle the

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[34] C. Vincent Tao, Zlatanova Sisi, and Prosperi David, "3D Data Acquisition and Object Reconstruction for AEC/CAD." *Large-Scale 3D Data Integration: Challenges and Opportunities*. (2005),.

[35] Robert Warden, "Towards a New Era of Cultural-Heritage Recording and Documentation." *APT Bulletin* 40 (3/4): (2009), 6.

[36] English Heritage. *3D Laser Scanning for Heritage (second edition): Advice and guidance to users on laser scanning in archaeology and architecture.* Edited and brought to press by David M. Jones. Swindon, (UK: English Heritage Publishing, 2011), 10.

sphere is viewed from, it will always look like a circle, thus it can always be registered as a target in the scan. The more references between scans using targets help ensure a more accurate registration process.

Accuracy and Completeness

Accuracy of the 3D laser scanner was discussed above; however, accuracy and completeness go hand in hand. One aspect of a site that is often important is the color of objects or elements in the site. However, even when 3D laser scanners "are able to capture the 'color' (for example by mapping photos over the surface), in almost all cases this leads only to the acquisition of the apparent reflected color, without considering the reflectance properties of the surface (e.g., its shininess)."[37] That is to say, that the colors are derived from the camera either built into the scanner, or mounted on the same tripod. The camera is only able to collect the color of the object as it appears, to the best of its ability. However, there could be factors, such as brightness of the light in the room from sunlight at different times of day, which could result in multiple scans of the same location being given different color values. This can be troublesome if the camera picks up the scanner shadow or other shadows, thus darkening the scans and not visualizing the true colors.

The phenomenon that occurs when the laser takes its measurements is different depending on the materials sampled, as mentioned above. These items could be made of materials or be positioned in such a way that an incomplete point cloud is created from the scan. Some of the many reasons that a point cloud can have holes or missing

[37] Marco Callieri, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Processing Sampled 3D Data: Reconstruction and Visualization Technologies." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (2011) 3:, 91.

data are the following: “presence of self-obstructing surfaces; presence of small cavities or folds; sections of the surface which are not cooperative with respect to” the 3D laser scanner being used.[38] There are many items that are in fact significant to a site whose materiality makes it hard to capture them. Some examples are “transparent or semi-transparent surfaces (like glass, jewels, and some stones); mirroring, polished and very shiny objects (like metals); fluff and fuzzy substances like feathers, furs, or some tissues.”[39]

Similar to fluff and feathers are leaves on trees and other vegetation. These items have the tendency to move constantly with barely any presence of wind. Because they are moving slightly in a scan, there will be points for all of the positions of the leaves, meaning that some points may have been missed if the leaves blocked them. Another element of a site that causes extra noise, extraneous data points, in the data is the movement of people, whether the scanning team or passersby. As long as these noise creators are moving faster than the laser, they will only appear as a thin line of points, captured as the laser swept past them. However, if they remain stationary, then the scanner will have to be repositioned to capture the data blocked by their bodies.

Data Management

Processing

Processing individual scans or range maps of a site into a complete point cloud requires a few steps. Of note is that before processing, a member of the acquisition team should either participate in the processing, or give detailed notes on the acquisition of the data on the site. This way if those processing the site have never

[38] Ibid. 78.

[39] Ibid. 91.

visited it, then they will be more likely to have a spatial understanding of what the site looks like or how the final product should look. Field notes from the field scanning team, as well as the planning drawings and sketches can be a vital tool to those doing the processing work. The steps of the processing phase can be broken down into three phases of processing, those phases that compose the 3D laser scanning pipeline are:

- Aligning the range maps.
- Merging of the aligned range maps to produce a single digital 3D surface (this phase is also called reconstruction).
- Mapping of color.[40]

An aspect that is not listed, but is integral in moving from the processing phase into the application or representation phase is that of cleaning up the model. The reason that cleanup is required is because the original 3D point cloud data captured by the 3D laser scanner "typically brings along noise points, floating points, dislocation of the mapping, holes, over sampling, insufficient sampling problems, and other issues."[41] As previously noted, one such issue that may arise is that of stray points created by the presence of people in the scanned environment.

Alignment

Because each individual scan has its own particular geometries, the first task is to bring the multiple positions into "one coordinate system using rigid transform or non-rigid transform."[42] During the scanning process, teams are most likely to move in a

[40] Ibid. 73.

[41] Mingquan Zhou, Guohua Geng, and Zhongke Wu, *Digital Preservation Technology for Cultural Heritage*. (New York: Springer, 2012), 15.

[42] Renji Li, Tao Luo, and Hongbin Zha, "3D Digitization and its Applications in Cultural Heritage." In *Digital Heritage Third International Conference, EuroMed 2010, Lemessos, Cyprus, November 8-13, 2010: Proceedings*, edited by EuroMed 2010 (2010 : Limassol, Cyprus) and Marinos Ioannides, (Berlin: Springer, 2010), 383.

particular pattern across the site. This pattern allows for easier "detection of the pairs of overlapping range maps" because the "3D acquisition is usually done by following simple scanning pose paths."[43] There are many methods to align the range maps that differ with the registration software. The most common is through the referencing of targets until the range maps are registered together so that the target points align. Despite the software differences "most alignment methods do require user input and rely on the overlapping regions between adjacent range maps," which can be targets or elements within the site.[44] There are three main types of registration: registration using targets, registration using similar points in range maps, and feature registration in which shapes such as cylinders and spheres are used to register scans together.[45]

Reconstruction

After alignment is complete, the image may look like a complete model, but in reality, all of the scans or range maps are still separate. This means that the overlapping scans contain many redundant data points. "This processing phase, generally completely automatically, exploits the redundancy of the range maps data in order to produce (often) a more correct surface where the sampling noise is less evident than in the input range maps."[46] When building the final point cloud, the software can

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[43] Marco Callieri, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Processing Sampled 3D Data: Reconstruction and Visualization Technologies." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (2011) 3:, 77.

[44] Ibid. 73

[45] Eugen Dutescu, *Digital 3D Documentation of Cultural Heritage Sites Based on Terrestrial Laser Scanning* Univ. der Bundeswehr München, Fak. für Bauingenieur-und Vermessungswesen, Studiengang Geodäsie und Geoinformation. (2006), 28.

[46] Marco Callieri, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Processing Sampled 3D Data: Reconstruction and Visualization Technologies." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (2011) 3:, 73.

give the option of also removing any points that have strayed from the norm, selectively assessing areas and finding where the excess points are located.

Color mapping

The point cloud, at this point in time, is only a measurement model. The points are colorized, as if they were pixels, by the application of photographs to the geometric representation. This step is important in the documentation of heritage because an accurate record of visual appearance is necessary to document and fully understand the resource.[47] Additional high-resolution photographs can be imported and overlaid onto the model for areas that require greater detail. For projects that are documenting works of art, this step would produce a more accurate and realistic 3D representation of the artwork. Additionally, the application of color images allows for a better understanding of the materials and conditions of the site.

Application

While the final point cloud model of a site is an interesting tool to use in experiencing and understanding a site, there are numerous applications for the point cloud data. However, some heritage projects have met challenges that “have occurred in the translation procedures and in the labor-intensive cost of converting the data into architectural drawings.”[48] While the point cloud model can be brought into other Computer Aided Design programs such as AutoCAD or programs like Revit, it often proves to be too much data for these programs to handle. There are plugins available in the scanner software or other programs that helps cut down on the amount of points

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[47] Ibid.

[48] Karen E. Hughes and Elizabeth I. Louden, "Bridging the Gap: Using 3-D Laser Scanning in Historic-Building Documentation." *APT Bulletin* 36 (2/3), (2005), 39.

being brought in from which wire frame models and drawings are produced. Another quicker technique is to produce high definition orthographic photos of the models, with necessary scales and measurements that can then be traced or drawn over in a vector program which aides in the conversion of point clouds to line drawings.

Another software application that can be used with the point cloud is Building Information Models (BIM). Capturing the as-built conditions of an existing building allows architects and engineers to get the exact dimensions of the building; after bringing into BIM the models can be "used in retrofit projects to ensure in-process quality control."[49]

There are many issues that can arise during this application phase that are important to plan ahead to avoid. The first of which is ensuring that the proper hardware is available to handle the large amount of data, as well as having the necessary programs to manage the data how the user intends. Another problem, arises in understanding who will be visualizing the data, and if these potential users have the skills or graphic expertise to manage the modeling. As long as issues like these are avoided, then the application possibilities depend on the user. Because even if the 3D scanning was completed for heritage purposes, the strict precision required for cultural heritage means that the processed model can be used for any field with an interest in the site. In fact, "due to accuracy of the 3D medium, we can think to use it as the main representation media, able both to represent an artifact but also to integrate other

[49] FARO. *Large Volume 3D Laser scanning Technology*. 11 July 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1901

multimedia information."[50] Meaning that not only can the processed model be used for projects, but it can also become a repository of information with the use of metadata.

Representation

While most fields require some form of visual representation to facilitate understanding of an idea, it is even more important with heritage to use this spatial information to describe or explain the history of a site or object.[51] The question of how the data be represented arises, and the solution depends on the initial project goals established in the planning assessment phase.

For cultural heritage however, there is one major protocol that must be followed in this step. In cultural heritage documentation, the task is to document what is existing on the site in that moment. This means produced models "should contain only sampled geometry", which dictates, "the use of software solutions which fill up the gaps is not allowed."[52] Nevertheless, since products can be interpretive or be used for future action plans on a site, some editing may still need to be done. Should this be the case "any editing action over the originally acquired data should be documented in the most evident way in order to make it possible to distinguish between ground truth sampled data and the parts that have been added or heavily edited by the subsequent geometric

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[50] Marco Callieri, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Processing Sampled 3D Data: Reconstruction and Visualization Technologies." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (2011) 3:,87.

[51] J-Angelo Beraldin, Michel Picard, Sabry F. El-Hakim, Guy Godin, Virginia Valzano, and Adriana Bandiera, "Combining 3D Technologies for Cultural Heritage Interpretation and Entertainment." International Society for Optics and Photonics (2005).

[52] Marco Callieri, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Processing Sampled 3D Data: Reconstruction and Visualization Technologies." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks* (2011) 3:, 78.

processing phases."[53] This way no user experiencing the data can confuse the digital additions or modifications for the authentic original site.

A prime example of how the data can be represented is by applying colors to the scan by selecting a single plane, and assigning different colors depending on the distance from the created plane. This gives the user "the ability of 3-D imaging to detect and record unseen conditions that deviate from assumed as-designed or as-built conditions, such as sags and out-of-tolerance construction that may indicate structural problems."[54] Another way in which the data can be represented is through the use of 4D phasing. With the use of 4D phasing, "a project sequence can then be viewed as a one- to five-minute movie, at 20 to 30 frames per second, representing 90 days to 18 months of activity."[55] This means that if there are detailed records of a sites construction, the 3D model can be edited in a way as to systematically show the construction of the building over time. This may not be as precise as the actual construction, since no records are meticulous enough to garner the amount of details needed for a completely accurate 4D phased construction representation.

Data Archiving

A 3D representative model can in no way replace the embedded history and time that the real world site possesses. That is because cultural heritage sites are "unique and non-renewable while digital information about cultural heritage has the advantages

[53] Ibid. 92.

[54] Caroline R. Alderson, Beth L. Savage, Charles Matta, Calvin Kam, and Anne E. Weber, "Government Policy and Practice: Digital Conservation and Landscape Renewal." *APT Bulletin* 41 (4): (2010), 16.

[55] Ibid. 14.

of being permanently stored, and conveniently copied and shared."[56] In fact, there are two schools of practices with laser scanning, the scanning process as a whole and the practices used for archiving the digital data.

Storage

As mentioned in the literature review, the Historic American Building Survey is only accepting 3D laser scan data as a form of supplementary data. One of the main reasons is that the life of the scans is unknown, as well as the unknown lifespan of the file format itself. Every form of data has a lifespan, the best practice is to use the data form that has been proven to last the longest. In the case of 3D laser scanning data however, the longevity of the scan data is relatively unknown, whereas other mediums have been established over time, evidenced in Table 3-4.[57] However, with virtual data there is the chance of immediate degradation. A virus, a hard drive malfunction, many things could happen to cause the data to be corrupted.

Unlike photographs where degradation or loss can be caused by natural aging, wear and tear, or the reading hardware no longer existing, virtual data may only be affected by the third circumstance.[58] Digital data is ageless in the fact that it will not succumb to elements, unless the storage location itself comes to harm. The same applies with wear and tear; the only way the data could be distressed is if it becomes corrupted in some way.

[56] Dongming Lu and Yunhe Pan, *Digital Preservation for Heritages Technologies and Applications*. (Heidelberg ; New York : Hangzhou: Springer ; Zhejiang University Press, 2010), 8.

[57] Alonzo C. Addison, "Safeguarding heritage's Endangered Digital Record" In *New Heritage : New Media and Cultural Heritage*, edited by Janice Affleck, Yehuda E. Kalay and Thomas Kvan (London ; New York: Routledge, 2008), 34.

[58] Rudolf Gschwind, Lukas Rosenthaler, Roger Schnider, Franziska Frey, and Jeanette Frey, "Digital Image Picture Archives: Theory and Practice in Switzerland." *Digital Applications for Cultural and Heritage Institutions*, (2005), 123.

The possibility of increasing the digital data lifespan increases rapidly if some simple planning and safety measures are taken. These measures, proposed by Rudolf Gschwind et al., were set forth for the preservation of digital image picture archiving, but are pertinent for digital 3D laser scan data as well:

- The medium used must demonstrate a lifetime of over 10 years.
- The medium should possess a system lifetime which is as high as possible.
- The medium must be usable with all hardware platforms and readable regardless of the operating system.
- The medium should be as tolerant as possible regarding changes in reading equipment; that is, it should be readable not only on the equipment on which it was written.
- The media and formats should have the highest possible redundancy. [59]

These guidelines are trying to be met by the creation of the E57 file format, expounded upon below. Nonetheless, it is particularly important for users of 3D laser scanning technology to have a backup strategy in place before the scanning even begins. In addition, a periodic storing and migration of both the raw scan data, and the project data needs to be laid out and followed on a regular basis. Because one small error on a team member's part could possibly erase an entire project or projects.

Metadata

In regards to metadata, it is important to at least answer *the who*, *the what*, *the where*, *the when*, *the why*, and *the how* in respects to the site. For *the who* fields, it is important to note who the scanning team comprised of, as well whom the documentation was done for. In *the what* fields, information can be input pertaining to the construction materials used, the techniques used, the history of the site, even the

[59] Ibid. 126.

reason for the sites significance. As for *the where* fields, Geo Positioning System coordinates can be input to accurately describe the exact locations around the site, as well as any physical addresses for the site. *The when* fields need to contain information on the dates the documentation occurred, as well as information regarding the processing of the site that are significant. For example, if after documenting the site, a piece is destroyed, this can be noted in the when section, describing in detail the date and time of the incident. *The why* sections can contain more information on why the particular site was selected, as well as why certain acquisition techniques were used for specific portions of the site. *The how* section can be used to describe the planning phase, the acquisition techniques, even the standards used in the technology assessment. Additionally to these sections, hyperlinks can be placed in the metadata to link to other resources that may be pertinent to the site. Each site will be different, and may require more fields for the metadata to accurately describe the 3D model. However, as long as these basic categories exist in the metadata then the metadata can be linked or shared in such a way that it can become part of "an expanding global, multilingual and multi-national network," resulting in a free and open information system.[60]

File Formats

There are many file formats that the finished 3D point cloud model can be exported or saved in. When the file is to be worked on further in applications such as Revit or Rhyno, it can be exported in .vrml or .igs formats. However, for long-term data

[60] Dimitrios K. Tsolis, George K. Tsolis, Emmanouil G. Karatzas, Dimitrios A. Koutsomitropoulos, and Theodore S. Papatheodorou, "Copyright Protection & Exploitation of Digital Cultural Heritage." *Digital Applications for Cultural and Heritage Institutions*, (2005), 190.

management, there has been the creation of a new file format called E57, represented as .e57. The American Society for Testing and Materials (ASTM) created an E57 standards committee in an effort "to develop standards for 3D imaging systems for applications like surveying, preservation, construction, etc."[61] The standards committee produced criteria and specifications pertaining to every aspect of the file format, to ensure that it has a longer longevity. The broad definition of the E57 file format is as follows:

> An E57 file is capable of storing 3D point data, such as that produced by a 3D imaging system, attributes associated with 3D point data, such as color or intensity, and 2D imagery, such as digital photographs obtained by a 3D imaging system. Furthermore, the standard defines an extension mechanism to address future aspects of 3D imaging.[62]

Not only does the format ensure that it can be forwards compatible, and therefore readable by newer devices, and not lost over time, but it allows for the inclusion of aspects that have yet to be realized in regards to data imaging. With all 3D laser scanning systems conforming to this file format standard, it will ensure that the data is not lost because that particular hardware/software combination went into disuse.

[61] Fabio Remondino, "Accurate and Detailed Image-Based 3D Documentation of Large Sites and Complex Objects." *Digital Imaging for Cultural Heritage Preservation: Analysis, Restoration, and Reconstruction of Ancient Artworks, F.Stanco, S.Battiato and G.Gallo, Eds.,* (*Boca Raton*: 2011),132.

[62] "ASTM E2807-11 1.2 Standard Specification for 3D Imaging Data Exchange, Version 1.0," Book of Standards Volume: 10.04, DOI: 10.1520/E2807-11.

Table 3-1. List of laser classes in the United States

Class	Description
Class I	Not hazardous for continuous viewing, or access to radiation is prohibited.
Class II	Visible light lasers that can cause damage if viewed directly for extended periods of time.
Class IIa	Visible light lasers not intended for viewing. Eye damage can be caused if viewed directly for more than 1000secs (16.67 min).
Class IIIa	Not hazardous if viewed momentarily. Damaging if viewed through collecting lenses.
Class IIIb	Hazardous to eyes and skin if viewed directly.
Class IV	Hazardous to eyes if viewed in any way. Fire hazard. Could cause skin burn.

Contents from Angelopoulou, Elli and John R. Wright Jr. 1999. "Laser Scanner Technology."

Table 3-2. List of laser classes in Europe (EN) and Internationally (IEC)

Classes	Description
Class 1	This class is eye-safe under all operating conditions.
Class 1M	This class is safe for viewing directly with the naked eye, but may be hazardous to view with the aid of optical instruments.
Class 2	These are visible lasers. This class is safe for accidental viewing under all operating conditions. However, it may not be safe for a person who deliberately stares into the laser beam for longer than 0.25 s, by overcoming their natural aversion response to the very bright light.
Class 2M	These are visible lasers. This class is safe for accidental viewing with the naked eye, as long as the natural aversion response is not overcome as with Class 2, but may be hazardous (even for accidental viewing) when viewed with the aid of optical instruments, as with class 1M.
Class 3R	Radiation in this class is considered low risk, but potentially hazardous. The class limit for 3R is 5x the applicable class limit for Class 1 (for invisible radiation) or class 2 (for visible radiation).
Class 3B	Radiation in this class is very likely to be dangerous. For a continuous wave laser the maximum output into the eye must not exceed 500mW. The radiation can be a hazard to the eye or skin. However, viewing of the diffuse reflection is safe.
Class 4	Radiation in this class is very dangerous, and viewing of the diffuse reflection may be dangerous. Class 4 laser beams are capable of setting fire to materials onto which they are projected.

Contents from FARO. Laser Classification. 29 August 2011. Available from: FARO: http://www2.faro.com/site/resources/details/502

Table 3-3. Comparison of 3D data collection approaches

Performance	Image-Based (Satellite)	Image-Based airborne)	Image-Based (ground)	Point Cloud-Based (airborne)	Point Cloud-Based (ground)
Accuracy	Low	Medium/High	High	High	High
Resolution	Low	Medium/High	High	Medium	High
Turnaround Time	Fast	Medium	Low	Medium	High
Cost	Low	Medium	High	High	High
Texturing	Low	Medium	High	N/A	N/A

Contents from 3d data acquisition and object reconstruction for aec/cad by C Vincent Tao in Large-scale 3D Data Integration: Challenges and Opportunities

Table 3-4. Data Longevity

Image	Medium (type of Record)	Lifespan (in years)
	Stone (e.g. Monument)	1000s (millennia)
	Paper/Wood (e.g. Drawing, Wooden structure)	100s (centuries)
	Magnetic/Optical (e.g. CD, disk, tape)	10s (decades)
	Encoding (e.g. VRML or JPEG data format)	1s (years)

Contents adapted from Alonzo C Addison Vanishing Virtual. Images 1, 2, and 3 courtesy of PublicDomain.com. Image 4 courtesy of Envision Heritage team.

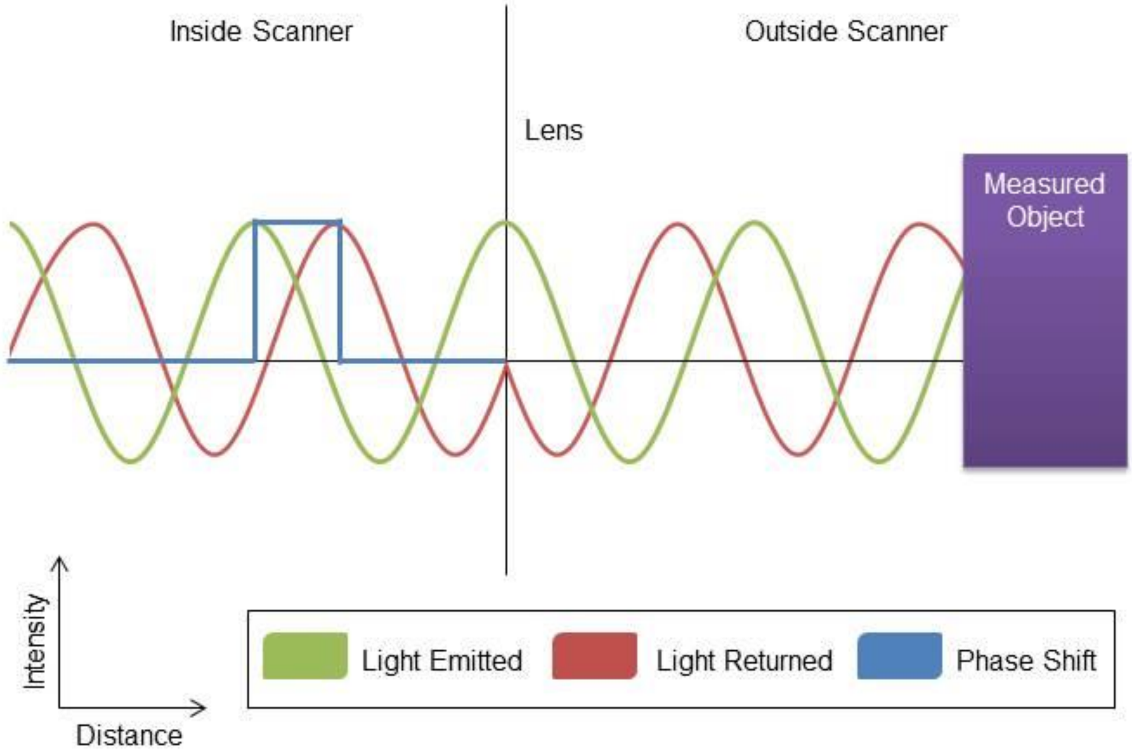

Figure 3-1. This diagram represents how the process of phase shift measurement occurs. (Adapted from FARO. Phase Shift Measurement and Time of Flight Measurement. 25 April 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1772). Image courtesy of Envision Heritage team.

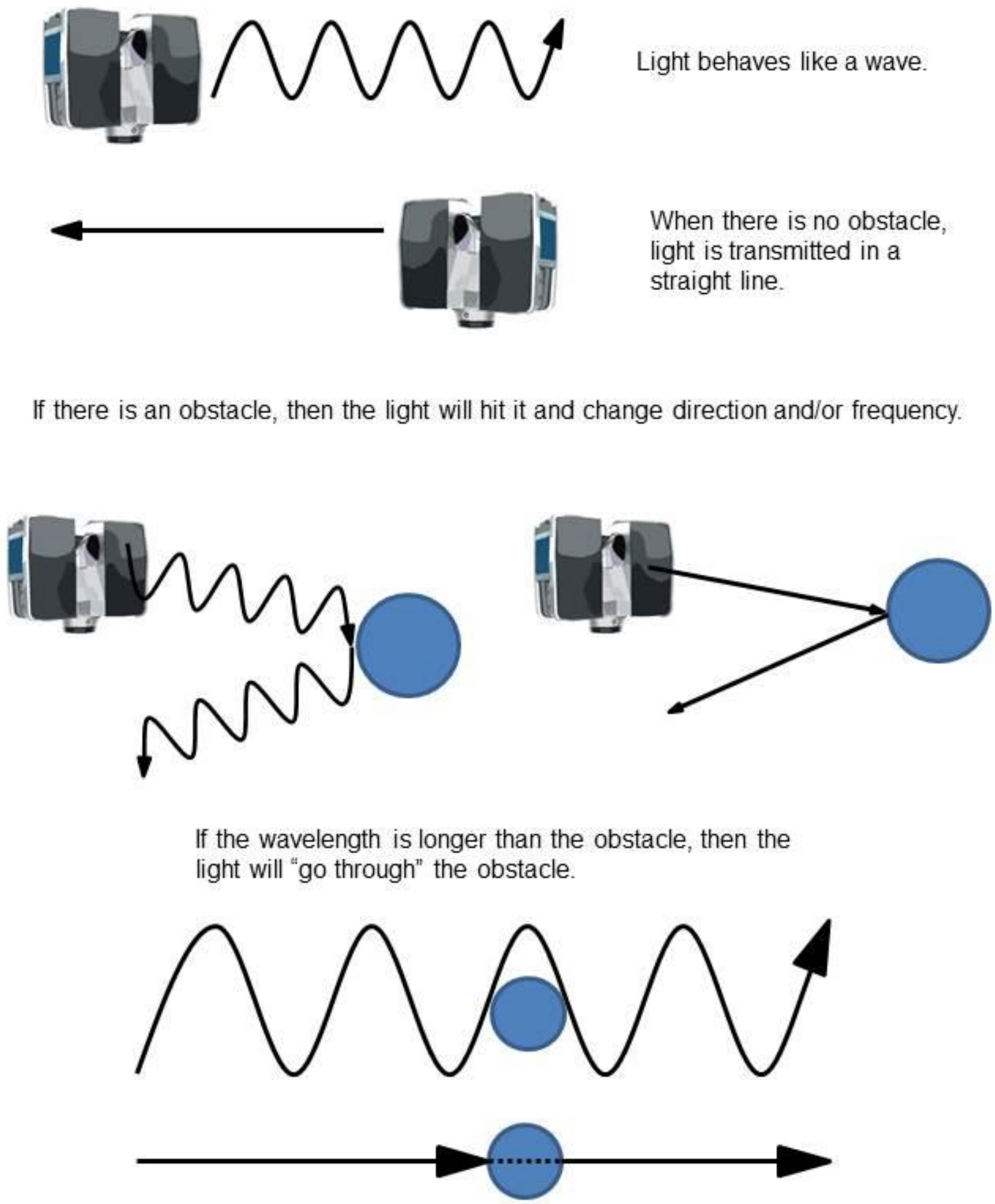

Figure 3-2. Principles of laser light. Adapted from Angelopoulou, Elli and John R. Wright Jr. 1999. "Laser Scanner Technology." Image courtesy of Envision Heritage team.

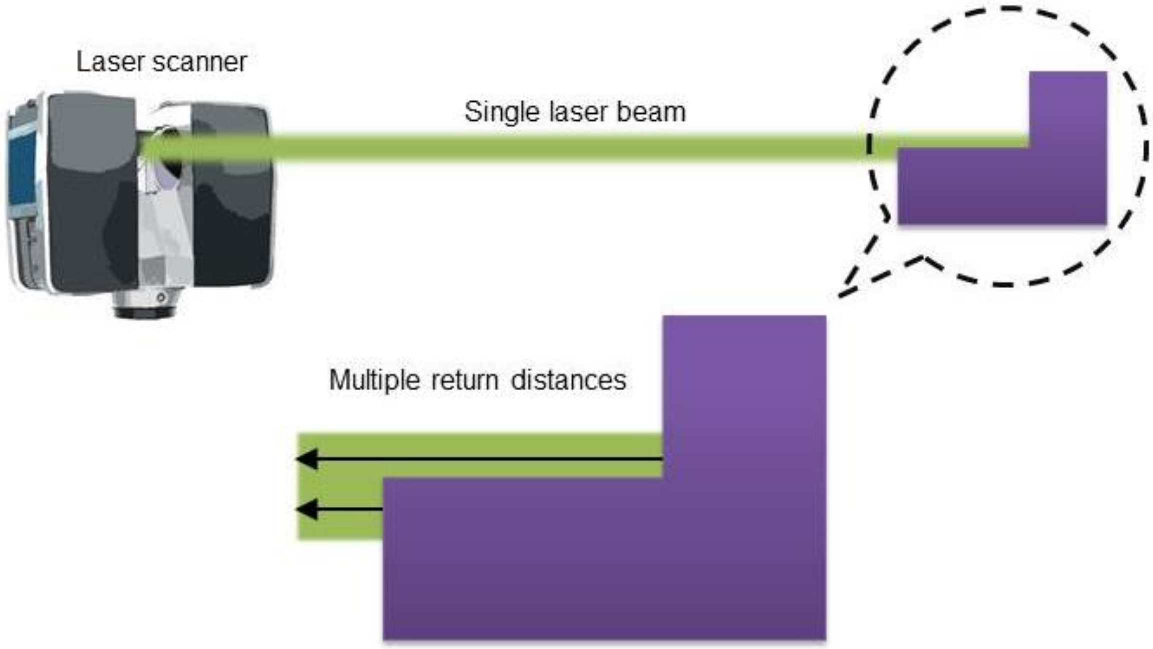

Figure 3-3. Measurement inconsistencies diagram. Here the inset shows that although you have multiple return distances, the measurement is determined by the center of the beam, which would in this case be the closer point. Image courtesy of Envision Heritage team.

CHAPTER 4
CASE STUDIES

The following case studies were selected because they represented different challenges for their documentation. One challenge was to determine the appropriate techniques for documenting heritage sites that ranged from the early 19th century to sites constructed in the recent past roughly fifty years ago. These case studies represent sites whose use has remained constant over time, whose use is amidst change, and whose disuse has caused a call to action. The materiality of the sites is similar in some cases, specifically wood construction, however within the sites that have this type of construction, they are differentiated by the fact that one of the sites also includes concrete and brick masonry construction buildings. The third site is also concrete construction, but the façade of the structure changes over time by the application of graffiti similar to how the cedar shingle facades of the wood construction age into their iconic gray color. The only constant amongst these sites was that documentation was required, and 3D laser scanning was a viable toll to be used to complete the documentation process.

Miami Marine Stadium

This first case study is a midcentury modern stadium, designed with a cantilevered fold plate roof. It is located just off Rickenbacker Causeway in Key Biscayne. The structure is mainly constructed out of poured in place concrete, which at times are only a few inches thick. The Commodore Ralph Middleton Munroe Miami Marine Stadium is 326 feet long east to west and 126 feet north to south.[1]

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[1] *Designation Report: Commodore Ralph Middleton Munroe Miami Marine Stadium.* By Jorge L Hernandez for Dade Heritage Trust and Friends of the Marine Stadium. 2011.

History

Cuban architect Hilario Candela designed the marine stadium as a sculpture that also provided cover. This stadium, completed in 1963, was the first venue for powerboat racing in the United States. Since then, the venue has been host to many other events, including boxing, water shows, church services, campaign rallies, and community events. The stadium was also used as a venue for musical performances that spanned multiple genres, and included such artists as Jimmy Buffett.[2] The stadium contains 6,566 seats from which spectators could view these events, all while covered by a poured concrete cantilevered fold plate roof.

In 1992, Hurricane Andrew damaged the stadium. City engineers condemned the structure, and it was left to deteriorate. In 2006, the City planned to demolish the structure, but public outcry waylaid these plans. Two years later, it was designated a local landmark for the city of Miami. In 2009, Miami Marine Stadium was listed as one of the America's "11 Most Endangered Historic Places" and in 2010 the World Monuments Fund selected the building for its biennial "Watch List."

Current Situation

This iconic stadium is now covered in graffiti and used by thrill seekers for parkour. "Now, though, a dedicated and determined group of preservationists, aided by the National Trust for Historic Preservation, is tantalizingly close to breathing new life into the stadium after five years of effort."[3] Currently, there are plans to develop a

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http://www.historicpreservationmiami.com/pdfs/2011%20designation%20reports%20updates/Miami_Marine_Stadium-Designation_Report.pdf

[2] Mark Humphrey, *The Jimmy Buffett Scrapbook* (Citadel Press 2000).

[3] Carlos Harrison, "Miami Romance: Saving South Florida's Iconic Marine Stadium." *Preservation*, Spring, (2013), 26.

fundraising strategy as well as a viable operational plan for the stadium. The Friends of the Miami Marine Stadium plan to bring this site back to its former splendor, with the Heat Group secured to run it after project completion.

Documentation Practices

The following sections depict the procedures followed by the documentation team to accurately and efficiently capture the Miami Marine Stadium site. The approach was informed by the best practices stated in the literature review as well as in the methodological breakdown described in Chapter 3. The documentation practices continue to follow the breakdown established by Vlahos mentioned in the beginning of Chapter 3.

Planning

For this project, the documentation team worked with the Friends of Miami Marine to develop the initial project goals. The goals stated that the final deliverables would be the project point cloud, the creation of photo-realistic sections and perspectives, and the production of Historic American Building Survey (HABS) quality line drawings, and a video flythrough. The reasoning behind these choices was based upon the fact that there existed no existing conditions drawings of the site. Additionally, it was intended that the site was to be rehabilitated in the near future, requiring the site to be understood as it currently stood. Additionally, the materials produced could be used in the fundraising effort to raise awareness of the site. The documentation team proposed documenting the site using a Faro Focus^{3D}. It was felt that with this technology; most of the site could be documented, with a few exceptions that were identified during the site assessment phase.

Site assessment

In preparation for data capturing, existing documents of the site were acquired. From these original line drawings, the documentation team selected locations for targets and scanner locations. Additionally, the documentation team used Google Maps to assess the roof plan of the structure, and ascertain how many scans it should take to document the fold plate roof. Using Google, and an initial site visit, the documentation team was able to get a feel for the size of the site, and determine exactly how many days of scanning would be required to document the site. The angular rise of the site meant that to achieve a common point resolution scanning would occur at different resolutions throughout the site. Additionally, the documentation team estimated that to accurately document the site would require over one hundred scans. To record this number of scans at multiple resolutions, the documentation team felt that three full days of scanning would be required. Because of the scale of the site, the documentation team felt that the Faro Focus^{3D} was an optimum choice, with its ability to document both exteriors and interiors with ease, as well as being a very portable device.

Because the Faro Focus^{3D} works by line of sight, the documentation team had to devise a scanning strategy that would document as much of the structure as possible, despite the existence of the original, fixed seating. To assess the minimum number of rows between scanning locations to document the structure, the documentation team did test scans on a nearby stadium. Using the University of Florida's Ben Hill Griffin Stadium, nicknamed the Swamp, the documentation team performed scans of the seating at intervals of three, four, and five rows at a time, as shown in Figure 4-1. From these scans it was determined that a scanner could be placed at intervals of every five rows to sufficiently document the concrete structure and floor of the stadium.

Additionally, the documentation team assessed the existing site conditions during the planning phase. It was determined from photographs and site visits, that there was an abundance of vegetation on the exterior sides of the stadium, blocking much of the structure. Furthermore, because the site projects out onto the water, it was determined that it would be impossible to document portions of the site that were out of the line of sight of the scanner, when it was placed on the edge of the side of the structure that faced the water. These portions included the front edge of the lower row platform of the stadium, and the concrete columns that supported it in the water. In addition, the documentation team felt that the graffiti was an important part of the structures history, so all efforts would have to be used to ensure that target placement did not obstruct this feature.

The documentation team had to plan for access to the site itself, as well as portions of the site inaccessible without equipment. The documentation team was let into the site every morning, by way of unlocking the chain link gate that surrounded the site. Additionally to document the roof, the team had to access it. Originally, access to the roof was achieved through a roof hatch in the press box. However, as the metal and plywood floor had given way over time, it was decided that it would be safer to access the roof using a boom lift. As mentioned above, the issue of the location of the site in relation to the ocean proved to be a planning hurdle. With the current equipment and technology of the documentation team, it was necessary to forgo scanning parts of the structure that could only be seen from the water.

From all of this it was decided that three full days would be required to document the site using the 3D laser scanner. This plan was of course weather permitting, because the site is mostly open to the environments, and therefore the scanning team could not designate days set aside to document interiors if it the weather did not permit exterior scans. The three days were split into documenting the roof and concession side of the structure, with the remaining two days documenting the seating deck, and any parts that had not been documented. It was also felt that the documentation of the exteriors of the small rooms within the structure would be enough, unless more time was available after documenting the other features.

Technology assessment

For the purposes of the projects presented in this thesis, the laser scanner used was a Faro Focus^{3D}. However, because it was the only scanner, the documentation team took into account the technology assessment of the scanner well before the sites were chosen. Therefore, the sites would not be found to be lacking in proper documentation because they were chosen based upon the technology assessment, rather than assessing a site to find that the current technologies were not capable of thorough and accurate documentation. Because of this, this first case study includes a complete technology assessment, while the others only briefly cover the benefits to the respective case sites.

The Faro Focus^{3D} was the laser scanner chosen to aide in the documentation of this site. Measurement is achieved by the Faro Focus^{3D} using a distance module that calculates the phase shift of the laser light.[4] Faro, the company that created the scanner provides a tech sheet, which breaks down the specifications of the scanner,

[4] FARO. *Phase Shift Measurement and Time of Flight Measurement*. 25 April 2012. Available from: FARO: http://www2.faro.com/site/resources/details/1772

which can be found in Appendix A.[5] A phase shift scanner was used because it provided greater accuracy for the projects at hand than the accuracies available with a TOF scanner. Additionally the range of the laser scanner is 150 meters, or relatively 492 feet, ensuring that data can be accurately captured within this distance. Additionally it is recommended that target be no more than 50 meters, or 164 feet, from the scanner to ensure accuracy in the registration process. The Faro Focus3D is able to rotate so that it captures points in 360 degrees radially and 305 degrees axially(Figure 4-2). Additionally the range of error for this machine is +/- 2mm, which is significant in cultural heritage where an error to within seven hundredths of an inch is acceptable. During the scanners 360 degree rotation, the first 180 degrees the scanner scans the environment, the additional 180 degrees are allotted to the camera to take color images, which can later be applied to the point data.

Safety when using the laser is a main concern, which is why it is important for the documentation team to know the classification of the laser, and the proper steps that, must be taken to ensure its safe use. The Faro Focus^{3D} is classified as a class 3R laser. Radiation in this class is considered low risk, but could be potentially hazardous. It is important to note, "The class limit for 3R is 5x the applicable class limit for Class 1 (for invisible radiation) or Class 2 (for visible radiation)."[6] Therefore, a class 3R laser is likely to emit between one and five mW during normal operations. Additionally, as Class 3R is a European standard of classification, it is important to know that class 3R

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[5] FARO. *Faro Focus^{3D} Features, Benefits & Technical Specifications*. 22 April 2013. Available from: FARO: www2.faro.com/site/resources/share/944

[6] FARO. *Laser Classification*. 29 August 2011. Available from: FARO: http://www2.faro.com/site/resources/details/502

is similar to class IIIA in the US regulations.[7] The definition in the US for this level of classification is for a laser that is not hazardous if viewed momentarily, but that can be damaging if it is viewed through collecting lenses.[8]

To address the issue of eye safety, the scanner enables the user to evaluate the risk depending on the density or resolution of the required scan. This is due to the fact that "the software to control the scanner shows the actual valid eye-safety distance."[9] This information is provided in measurements both axially and radially in regards to the scanner location. Moreover, the measurements provided take into account "that 'eye-safe' is applicable to the whole optical spectrum from 180nm to 1mm wavelength, not just in the retinal hazard range of 400nm to 1400nm."[10]

Furthermore, the Faro Focus[3D] was chosen because of its size and portability. The lightweight scanner and small tripod allowed for quicker setup times as well as quicker repositioning for the next set of scans. This would not have been possible with other scanners that can sometimes require two people to assemble the scanner at one scan location. Still, the size of the scanner allowed it to be positioned in small and cramped locations, which would have been too tight for other scanners.

The costs associated with the documentation include not only the scanner but also the software, as well as housing for the documentation team near the site. Some minor costs in comparison to those for purchasing the scanner included parking, hotel

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[7] Ibid.

[8] Elli Angelopoulou and John R. Wright Jr., "Laser Scanner Technology." (1999), 9.

[9] FARO. *Laser Classification*. 29 August 2011. Available from: FARO: http://www2.faro.com/site/resources/details/502

[10] Ibid.

accommodation, tolls to access the island the site is located on, etc. While the scanner and software themselves were relatively expensive, being roughly $45,000, these costs are only a one-time payment, with this equipment used to document multiple sites.

Scene, the proprietary software associated with the Faro laser scanner, allows for the importation of individual scans so that they may be processed into point clouds. The software loads scans, and presents them in a folder tree which makes grouping the scans easier for the user. In the software, the user completes the main processing portion of the data management phase. The individual scans or range maps are aligned, and combined into the single point cloud model. Additionally the color images can be applied to the scans in this software. Some aspects of the application and representation portions of the data management phase can be conducted in this program, but often times, these steps are done with other software programs whose use is necessitated by what the final products to be created were established in the project planning phase.

Data gathering

The documentation team decided that paper checkerboard targets would be used to register the scans together. However, the documentation process inevitably resulted in these targets being less useful that initially intended. Because of the harsh winds that occurred during the days in which the site was documented, the paper targets were often blown off the wall, despite being taped down completely. Once a target had fallen, it could not be placed back up, because then any future registration would not register the scans to the correct point. Therefore, it was decided on site, that the concrete forms would have to provide the planar surfaces required for data registration.

During the documentation process, scans were loaded onto the computer to assess whether areas were being documented completely, and to ensure that the desired accuracies were achieved. The scanning plan required the team to reach the roof through the use of a boom lift, pictured in Figure 4-3. While scanning the roof, it became apparent that the internal drainage systems had been clogged, and thus some portions of the fold plate roof retained water. This water was noted to cause the laser light to not reach the roof surface under the water, and thus no data was collected on these areas. Additionally, the water acted as a mirror in some instances, producing data of the reflection from the water, but represented along the initial angle and final distance of the beam, an example of which can be seen in Figure 4-4. The documentation team also noted that the angle of the roof was too steep to place the scanner on the folded plate structure at a height that would allow for the documentation of the top of the wall separating the short concession side of the roof with the long seating deck side. Because of this, scans had to be taken on the basins formed by the plates, far enough back to capture the wall from the other basis. This resulted in the fact that the highest plane of the dividing wall could not be documented.

Other environmental factors that created a loss of data in the acquisition process included the location of the sun. In Figure 4-5, the sun is clearly visible as a hole in the data, a hole, which because of its closeness to the structure, resulted in missing data. Sunlight causing loss of data because of the competing wavelengths of light between the scanner and the sun resulted in the company that created the Faro Focus^{3D} to create a newer model that uses a different wavelength that is not affected by that of the sun.

Additionally as mentioned earlier, the documentation team scanned the seating deck up each aisle, at roughly every fourth or fifth row, to ensure that there were no holes in the data caused by the seats. The abundance of columns and other structural forms in the site also necessitated increased scan locations that had been plotted out by the documentation team during the planning phase. This was needed to ensure that all aspects of the geometrically significant columns were captured with as few scans as possible. These scans at different locations around the columns were able to capture the multifaceted shape of the columns without resulting in holes in the information, as evidenced in Figure 4-6.

It was determined that different areas of the site would require different resolutions for documentation. The scans performed on the roof, and on the concession side were nine-minute scans with a resolution of 43.7 Mega points (MPts), meaning a density of around 5.6mm. Whereas the lower seating deck was comprised of scans that were roughly five minutes in length resulting in a resolution and density that remained the same. As the rows went up, they became closer to the ceiling of the cantilevered roof. This meant that upper seating would only require roughly three-minute scans resulting in a density of 11mm, meaning a resolution of around 10.9 MPts. Additional scans were done at five-minute lengths for areas that linked concession to the seating deck, because the areas were small. Scans were additionally completed at the two corners of the seating deck at a resolution of 174.8 MPts, meaning a density of around 2.8mm, resulting in a scan length of thirty minutes to try to capture the site and context from these far points. These density ratios in millimeters are given for objects that are ten meters from the scanner, therefore if objects are closer, the density increases.

Data management

The scans collected by the documentation team were brought into Scene, the proprietary processing software associated with the Faro Focus^{3D}. Within Scene, the scans were arranged into different clusters to make the registration process easier. All of the concession scans were grouped into one folder, the roof scans were split into two folders depending on if they were taken on the long or short side of the roof, and the seating deck was split into an east and west folder, with these folders being split into upper and lower seating folders. This was done to make the processing much easier to handle.

Where checkerboard targets existed in the scans they were registered and made based upon location. However, because of the winds mentioned earlier, there existed only so many targets in the scans. Therefore, it became important to register using similar planar surfaces within the site itself. While this process was more time consuming, it was necessary to proceed this way. It is important to note that a naming technique is required, so that the registration process runs smoothly. This way multiple users can work on a project, with the same naming conventions, and produce an aligned point cloud system. Otherwise users may be labeling registration elements differently, and thus the elements would not register as the same in the program. Additionally with a site such as the Marine Stadium, repetitive elements produce an easier naming convention, where the north side of the first column and south side of the second column could be referenced as n1c and s2c respectively. Again, it is important to document this method of shorthand so that others on the processing team can understand and follow through with the naming technique.

Once all of the range maps from the individual scans had been aligned, it was time to convert them from multiple scans into a singular point cloud model. This process requires the scans to be loaded, and added to one another, so that repetitive points can be removed during the point cloud construction. This is important, because an oversampling of the exact same data point is not required, and can often slow the computer down when viewing or editing the model. Once the project is a single point cloud, clipping boxes were used to hide portions of the site to better understand it.

In understanding the site, however, colors of the objects within the site are necessary. Pictures were applied during the point cloud generation phase of the data management process. Subsequently, the team encountered a technical bug within the software that has affected the images that were applied to the scans to represent the site in color. Where the old adage was that the early bird gets the worm the newer version should state that the early adopter gets the bugs. Somehow, during the application of the pictures, a bug arose that caused the images linked to the scans to no longer be linked. This meant that scans that had been colored, reverted back to gray scale images, and could no longer access the original images. Although these images were in fact still available, and if the entire processing procedure were begun again the images were available. It was found that a work around to color the images, while working temporarily, would result in the images being lost again the next time the project was opened. Working with the software developers, a solution to this problem will eventually be found, but the problem currently persists in the documentation team's projects.

Despite the lack of color, the 3D point cloud model of the site could still be used to produce some of the required deliverables. Using clipping boxes within the Scene software, portions of the site could be hidden, while others remained visible. These boxes were then used to produce orthographic images of sections and plans of the site. An plan of the site as viewed from above was created, shown in Figure 4-7, and shows areas of the roof where the water pooled, resulting in no points collected in those areas. Additionally, a section was produced, pictured in Figure 4-8, which better depicts the intricate forms of the Marine Stadium. The point cloud, as well as the images produced from it, is currently being brought into AutoCAD to produce line drawings of the site. The representation of the site through the 3D point cloud model is not perfect. There exist many points created from elements such as people and plants within the site that can be further removed to produce cleaner model. With the successful application of pictures, a realistic flythrough will be created using either the Scene software of another application called Pointools.

Data archiving

Data storage of this project and its associated files can only currently be described as short term. The current means of storage are threefold. First, the data is stored on the computer on which the data was processed and continues to be processed. Secondly, the data is stored on an external hard drive, which is updated with the new files after any major work occurs. Lastly, the files are saved onto a University of Florida server.

In terms of metadata, this project only contains the basic metadata that can be preprogrammed into the laser scanner, and applied to the produced scans. This data includes who the documentation team is, the site being documented, a rough GPS location, and any additional information the team may have entered. As of yet however, there has not been many strides to add additional metadata to the 3D point cloud, although some proposed options include:

- Field notes on the existing conditions of elements of the structure
- Links to previous studies conducted on the site
- Links to existing documentation of the site
- Current cost analyses of elements in the site
- Personal information submitted by users pertaining to the site

These elements are not necessary, but may be used later by other parties who may find other uses for the 3D point cloud of the site.

Currently the file formats being used for the data are mostly proprietary formats. However, these formats are read by multiple pieces of software, and are thus not limited to a single program. All of the raw scan data, before it was processed, or added into a project folder, is saved in the original .fls format, FLS meaning Faro Laser Scan. Additionally, the project folders are saved in an .fws format, which stands for Faro Workspace. Once the colors are able to be reapplied to the scans of the Marine Stadium, the final product will also be saved as an .e57 because E57 format is the preferred file format for laser scans because of its built in long term viability.

Maria Mitchell Washington Street Properties

The second case study involves two parcels that are now owned by the Nantucket Maria Mitchell Association. These properties are at 31 Washington Street and 33 Washington Street, Nantucket Town on the island of Nantucket, Massachusetts.

The parcel on 33 Washington St. contains a single building, whereas the other parcel contains three buildings. All four buildings, ranging from the late 1920s to the 1940s, are wood construction and clad with Nantucket's iconic cedar shingles.

History

Originally, the main structure on 33 Washington Street was constructed around 1928 as a summer residence that was lived in until 1979, when it switched to commercial use.[11] The largest and nearest structure on 31 Washington was constructed later as a residential property as well. The Kerr School of Art around the 1940s constructed the two remaining structures found on the site.[12]

Current Situation

At the time of documentation, the building on 33 Washington Street (Building 1) was being temporarily used as an art gallery. The Maria Mitchell Association has purchased the property so that it could be turned into a new natural science center and aquarium, that would replace the old facility that is currently housed across the street. The larger structure on the 31 Washington Street property (Building 2) is a residential home, and will have to be moved to make way for the new additions to the science center structure. The smallest structure on this property (Building 3) currently houses the office for Nantucket Bike Tours, while the remaining structure (Building 4) acts as a small residential apartment. These structures are planned to become exhibit spaces for the proposed Science Center.

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[11] Maria Mitchell Association. *Maria Mitchell Aquarium and Science Center: Design Portfolio 33 Washington Street.* Nantucket, MA: 2013. http://www.mariamitchell.org/wp-content/uploads/MMA_Design-Portfolio_02.26.13.pdf (accessed 26 August 2013).

[12] Ibid.

Documentation Practices

The following sections depict the documentation procedures followed by the documentation team to accurately and efficiently capture the Maria Mitchel Washington Street Properties.

Planning

In regards to this project, the documentation team consulted with the Maria Mitchell Association in order to develop the project goals. The goals stated that the final deliverables would be the project point cloud and the creation of photo-realistic sections and perspectives. No architectural drawings of Building 1 were known to exist, and as the building was to be renovated and partially demolished, an accurate record of the structure was required. The same principles were also applied to Buildings 3 and 4, which were slated to become part of the new science center. Building 2 was documented for the purposes of knowing the setting on the site, but was planned to be moved to make way for the science center expansion. Again, the documentation team proposed documenting the site using a Faro Focus3D.

Site assessment

In the case of these properties, there were no known existing drawings of the site plan or building interiors at the time of scanning. Therefore, the scanning team had to rely on site visits, as well as Google Maps to better understand the layout of the site. Using Google Maps, the documentation team planned the exterior scans of the buildings on the property. By contacting owners of the buildings on the property, the documentation team was able to ensure access to the three structures that would remain on the site. However, planning of the interior scans was decided to be done on site. This was in part due to the fact that it was unknown at the time how much artwork and installations would be in Building 1, and whether they would obstruct the scanner. To quickly document these small possibly cramped interior spaces, as well as the larger exterior spaces, the documentation team felt that the Faro Focus^{3D} was the best choice of scanner to complete the job.

Additionally, during the planning phase, the documentation team assessed the existing site conditions. From images, it was apparent that vegetation would be an issue, especially at the rear of Building 4. The documentation team also determined that work would have to be done over the course of two days. One day would be dedicated to documenting the exterior of the site, as well as the interiors of Buildings 3 and 4, while the other day would be used to document the interior of Building 1. Knowing that Nantucket weather is prone to dense fog and possible rain, the documentation team felt that the exterior should be documented on whichever day was predicted to be the clearest. Additionally, the documentation team had to ascertain which days would be best to enter the multiple buildings on the premises without hindering the day-to-day operations of those that used the site.

Technology assessment

As mentioned above, since one machine, the Faro Focus^{3D}, was used on all three case studies, the technology assessment was described in detail in the first case study. However, it should be mentioned here that the docking station for the battery that the scanner uses was found to be not functional. Therefore, the batteries had to be charged directly in the scanner, and thus the scanner had to be plugged in. This resulted in the scanner being plugged in during some of the final exterior scans of the site.

Data gathering

Paper targets were used to ensure that the scans could be registered to each other in the processing phase. It was decided that the first day of documentation would focus on the interior of Building 1. Therefore, the documentation team quickly assessed the interior space, and planned where exactly the scanner would be placed throughout the structure to capture as much detail as possible. Once scanner locations were known, it was up to the documentation team to place the paper checkerboard targets throughout the site ensuring that there were at least three points of reference overlapping within each scan. Additionally care was taken to place the targets on walls that would be visible from the front and rear door of the structure to ensure that the interior and exterior of the building could be registered together during the processing phase.

When applying targets to the exterior of the structure, it became apparent that the shingles created a surface that was not conducive to the placement of the targets. The weathered shingles did not allow the tape to be as adhesive as it was supposed to be. Therefore, in most cases, the targets were taped to features such as trim or windows where there were no shingles. If it was unavoidable, then more tape was used in an effort to ensure the targets stayed up long enough to be scanned. Additionally, areas, such as one of the sides of Building 4, the vegetation was so thick, that no targets could be seen by the scanner, which would lead to hand registration later during the processing phase.

For the purposes of this project, both the interior and exterior scans of the site were done in nine-minute scans resulting in a 43.7 MPts resolution, meaning a density of around 5.6mm at a distance of ten meters away. It was felt that this level of accuracy would ensure that enough detail was captured of the site for the current needs, as well as any possible future needs. During the documentation process, the team brought scans into the Scene software to ensure that there existed minimal holes in the data. The only area that was deemed incomplete was that of the roof, which was blocked from multiple angles by the chimney. Only a small portion of the roof was missing, and could be extrapolated from the parts that were documented. Additionally, documentation team members sketched the building facades (Figure 4-9), as well as buildings and their surrounding environments documented by the scanner (Figure 4-10).

Although most of the planning process insured that the documentation could occur without issue, some did arise. One issue was that scanning had to be stopped for the exterior, while a tractor regarded the gravel drive way and parking lot on the site. Additionally, a car very narrowly hit the scanner, as it was scanning from the driveway, and a resident pulled in to park on the portion of the site owned by them.

Data management

Once again, with this project, the scans collected by the documentation team were brought into Scene. Within Scene, the scans were arranged into four different clusters to make the registration process easier. All of the Interior scans of Building 1 were one cluster, the two interior scans of Building 3 were another cluster, the interior scans of Building 4 were another cluster, and the exterior scans of the site were the final cluster. Again this separation of scans into different cluster folders was done to make the processing much easier to handle.

The processing team was able to register the individual range maps or scans of the site together using the checkerboard targets. However, there were a few instances where the checkerboard targets were not enough to align the scans. In this case, some elements from the site and its context were used to aid in registration. The side of Building 4 for example was not able to see any checkerboard targets, however, the scan was able to capture points along roof and chimney planes on nearby structures. These were referenced within the scan done on the side of Building 4, as well as any other exterior scans that contained these elements. With these additional planar references, the range maps were able to be aligned correctly.

At this point, the multiple range maps were combined into the single point cloud. During this process, the color images taken by the scanner were also applied to the scans. It is important to note, that the same software bug, resulting in the loss of color to many of the scans, also affected this project. However, in this case, much of the interior spaces were able to retain their color, while the images tied to the exterior scans were no longer connected.

For photo-realistic sections and perspectives to be produced, the images created from the scans must have color information. Until the issue with colorization is resolved, the documentation team continued to produce images that help in understanding the site. In comparing Figure 4-11 and Figure 4-12, it is possible to view the site from an aerial perspective. In Figure 4-11, the documentation team used the option to make wall clear, thus enabling to see inside the building, as well as to make scan locations more apparent, whereas in Figure 4-12, the points are represented without any changes. Additionally, the documentation team was able to produce a site plan (Figure 4-13) that included Buildings 1-4.

Data archiving

Once again, the data storage of this project and its associated files can only currently be described as short term. The same three means of storage were used on this project as the Miami Marine Stadium project. However, there was a small hitch in the data storage process, because the protocols were not followed closely. Although the individual files had been save elsewhere, the actual project file was only saved in one location. This created a problem when during transport; the computer's hard drive became corrupted. Luckily, the information on the hard drive was recovered, and the data was saved by following the protocols correctly.

The same measures towards metadata and file formats used for the Miami Marine Stadium project were applied to this project. Additionally, in agreement with the Nantucket Maria Mitchell Association, the models and other products will be made available through the Association. That way the information is accessible to all interested in the Maria Mitchell properties.

Maria Mitchell Vestal Street Properties

There are six Maria Mitchell Association properties along Vestal Street. These include the Maria Mitchell Home (1770), the Observatory (1908), the Observatory Cottage, the Hinchman House (c. 1800), the Science Library (1920), and the student dormitories/administrative office. With the exclusion of the Science Library and the Observatory, the remaining buildings are all wood frames and clad with cedar shingles. The Observatory is a brick building, while the Science Library is part wood frame part concrete construction, and features a fireproof asbestos stucco finish.

History

The Maria Mitchell Home, located at 1 Vestal Street, was constructed between 1770 and 1830.[13] It was a residential property until 1902 when the Maria Mitchell Association was founded, and was purchased from the Mitchell heirs. This home features a later kitchen addition, as well as a caretaker's cottage that was added onto the back of the kitchen addition. The Observatory building was dedicated in 1908, and in 1922, an astronomical study was constructed that joined the Observatory to the Mitchell Home.[14] The Observatory Cottage was constructed later, with additions being completed after the 1987 HABS documentation joining the cottage to the observatory building. The Lydia S. Hinchman House, located at 7 Milk Street, was built in the federal style in the early nineteenth century for Thomas Coffin.[15] Lydia Hinchman, the founder of the Maria Mitchell Association, and first cousin to Maria Mitchell, "willed the property to her son with the request that it pass to the Maria Mitchell Association upon his death."[16] His death occurred in 1944, which lead the Association to accept the home, and later turn it into a natural science museum with staff quarters. The Science Library was constructed in in 1920 to house the permanent collection that came into

[13] Constance Werner Ramirez, "Swain-Mitchell House, 1 Vestal Street, Nantucket, Nantucket, MA," Historic American Buildings Survey Report (HABS No. MA-901). (Washington, DC: U.S. Department of the Interior, National Park Service, 1971).

[14] Sarah L. Gloss, Joanna E. Wyszatycki and Ricardo J. Viera, "Maria Mitchell Observatory, 3 Vestal Street, Nantucket, Nantucket, MA," Historic American Buildings Survey Report (HABS No. MA-1276). (Washington, DC: U.S. Department of the Interior, National Park Service, 1987).

[15] Susan Braselton, Lynn Crocker, Chris Sharples, Mark Voigt and Brian Walker, "Hinchman House, 7 Milk Street, Nantucket, Nantucket, MA," Historic American Buildings Survey Report (HABS No. MA-1287). (Washington, DC: U.S. Department of the Interior, National Park Service, 1987).

[16] Ibid.

existence in 1902 when the Association was formed.[17] It was not until thirteen years later that the safety of the collection came into question, and the fireproof addition was created. The final Maria Mitchell property is a residential home located at 2 Vestal Street, which acts as the Maria Mitchell Association student dormitories and administrative offices.

Current Situation

Little has changed to these properties on Vestal Street since their ownership was taken over by the Maria Mitchell Association. Historic home tours are given daily to those who visit the Maria Mitchell house. The Science Library is open daily to the public, as is the Hinchman house science museum. The observatory holds small demonstrations in the courtyard, and all of the student interns who help the Association perform its various activities use the dormitories.

Documentation Practices

The following sections depict the documentation procedures followed by the documentation team to accurately and efficiently capture the Maria Mitchel Vestal Street Properties.

Planning

The documentation team worked closely with Jascin Finger, the curator of the Maria Mitchell house, in order to develop the project goals. The final deliverables derived from the goals would be the project point cloud both with and without the Maria Mitchell house interiors, the creation of photo-realistic sections and perspectives, and HABS quality line drawings of floor plans. The reason for two project point clouds is

[17] Stacia A. Hummel, James A. Romer and Baeza, Miguel E. “Maria Mitchell Association, Science Library, 2 Vestal Street, Nantucket, Nantucket, MA,” Historic American Buildings Survey Report (HABS No. MA-1275), (Washington, DC: U.S. Department of the Interior, National Park Service, 1987).

because the interior of the Mitchell house, being a house museum, is private, and thus images of the interior must require approval from the Maria Mitchell Association. Therefore, a complete 3D point cloud model would be presented to the Association, while another lacking the interior scans would also be produced so that the Association could distribute it. Additionally, because HABS documentation had occurred for the interior of the Mitchell house in 1971, the line drawings from the scans would produce more accurate measured drawings than those completed by hand. Once more, the documentation team proposed documenting the site using a Faro Focus3D, because of its size, portability, and built in camera.

Site assessment

Having previously visited the site, the data capture planning was relatively easy for the documentation team to complete. The existence of the HABS site drawings (Figure 4-14) produced by the Preservation Institute Nantucket, enabled the documentation team to plan the majority of the exterior scans. However, the dormitories as well as the observatory cottage had changed layout since the creation of the drawing. Therefore, the documentation team consulted Google Maps to plan the scan locations for these structures. Google Maps also gave the documentation team a better understanding of the current vegetation that surrounded the site, and that would have to be worked around.

Although the interior of the Maria Mitchell house had been documented by HABS in 1971, and the documentation team had visited the site before, the interiors still provided some difficulty in planning. This is because the team only had their memories to work off on the existing furniture and other pieces in the historic house museum. Therefore, the team mapped out that each room would have a minimum of one scan location in it if it were empty, but that since the rooms were filled with artifacts, they would often require two or more scans. Therefore, the data capture planning was finalized on site after a walkthrough of each of the rooms.

Target placement also proved to be a difficult task for the documentation team. The curator provided the documentation team with a specific painter's tape with the instructions that it could only be used on wood features such as doors, frames and moldings. The targets additionally could be placed on the floor, as long as they did not come into contact with the historic carpets. Targets were not allowed on the walls themselves because the wallpapers and finishes were deemed too fragile for the tape to be used on. This factor limited the placement of targets, and thus the documentation team had to be creative and efficient in their placement of targets.

Using the HABS site plan produced in 1987, the documentation team was able to garner a better understanding of the scale of the site. Fully aware of the scale of the site, it was decided that the documentation would have to span over three days. One day dedicated to the exteriors of the buildings on the southern side of Vestal Street, one day for the exteriors of the buildings on the northern side of Vestal Street, and one day for the interior of the Mitchell house. Because the northern side of Vestal Street was smaller, the additional time remaining after documentation of the exteriors was allotted to document the interiors of the Mitchell House.

To ensure that the roofs of many of the structures were documented, a higher vantage point was required. Therefore, scan placements were planned on the observatory addition, to capture the observatory dome, as well as the caretaker's cottage addition and the roof of the Science Library across the street. Additionally two scans were planned for the roof walk on the Mitchell House, to document the chimney, as well as the roof of the Hinchman house and other roofs not visible from the vantage point of the observatory addition. To capture the other side of the roof of the Hinchman house it was found that scanning locations across the street on Milk Street would provide sufficient vantage points.

Once again, with this case study vegetation was a hindrance to the documentation process. In some areas, large bushes acted as barrier walls, and thus scans had to be done on both sides to document the buildings. Additionally, the documentation team knew that some facades because they were covered in ivy, were not going to be able to be documented properly. The documentation team also worried that the dome of the observatory would prove to be too reflective for the scanner to register points from.

Accessibility to the site, and specific buildings was an issue that the documentation team had to address by working closely with the curator of the Mitchell House, Jascin Finger. Jascin had to get permission from the neighbor who lived behind the Science Library to document the building from the neighbor's backyard. The neighbor wanted as little disturbance as possible, so one team member very quickly documented the back wall of the Science Library in three scans without targets. Additionally Jascin received permission from the neighbors who owned the property abutting the back of the observatory and caretaker's cottage. The documentation was allowed to tape up paper checkerboard targets, so long as they were removed from the property promptly after documentation. These neighbors' acquiescence allowed for the documentation of the back of the buildings from a narrow alley around three feet wide.

The documentation team also encountered an issue that was caught and handled in the planning phase. This accessibility issue arose because documentation could not occur on August 1st, because this was Maria Mitchell's birthday, and a celebration occurred on the property on this day. Also of note, was that the documentation of the interiors of the Mitchell house had to be conducted while the home was being operated as a historic house museum. This meant that the documentation team had to plan which rooms would be scanned while on site to avoid the tour groups passing through the building. This meant that downstairs rooms were documented while tours went on upstairs, as well as rooms being documented while the tour skipped the room, to return once the scan had been completed.

As mentioned with the earlier Nantucket case study, the documentation team had to be prepared to document the exterior site during good days, and leave the interior site documentation for days that were more likely to have inclement weather. This ensured that should the need arise, the documentation schedule held some flexibility, and thus ensured that no time was wasted during the documentation process.

Technology assessment

As stated above in the first and second case study, since the Faro Focus^{3D} was the only laser scanner used on all three case studies, the technology assessment was described in detail in the first case study. Once more as mentioned above in the second case study, the charging dock was nonfunctional during the documentation process, but the scanning team was able to charge the batteries overnight in the scanner to ensure full batteries during the days for documentation.

Data gathering

On the first day of documentation, the weather was conducive to exterior scanning, and thus that is where the documentation team began. While team members placed targets on the southern side of Vestal Street, one team member along with the curator accessed the property behind the Science Library. Since no targets were used in these scans, it was important to ensure that planar surfaces were visible in the scans to make the processing phase easier on those processing the data. After this was completed, documentation continued starting with scans at the front of the Science Library. From there the team moved in an easterly direction documenting the back of the Hinchman house. The documentation team then moved to the west side of the Science library and continued documenting towards the dormitories. Working counterclockwise around the dormitories, the team captured all of the dormitories as well as the planar surface of the chimney of the Science Library that was visible in the first scans done without targets. From there the documentation team captured the side of the Hinchman house from across Vestal Street in. Then as planned, the front façade and roof were capture by two scans from across the street, followed by two scans up close.

The next day rain was predicted for around midday, so the documentation team took the opportunity to document the interior of the Mitchell house. The documentation started in the historic portion of the home in the root cellar. After completing scans in the cellar, the team moved to the first floor. The floor was documented in a clockwise pattern moving from the old kitchen to the birthing room, into the study, and out into the main hall. The arrival of a tour necessitated that scanning continue in the historic kitchen addition before scanning could be recommenced in the hallway. From there the team moved on to the second floor. Documentation began in the attic space above the kitchen addition before again moving clockwise through the house until returning once again to the hallway. From the hallway, the stairs to the attic were captured, and followed by the attic itself with care to document all sides of the chimney, as well as the nursery room. At this point, the weather cleared, and it was decided to complete the two scans from the roof walk to document the chimney as well as the roofs of the nearby structures (Figure 4-15).

On the third day, documentation began again with exterior scans of the caretaker's cottage and observatory and addition from the neighbor's yard. One target was placed on the neighbor's home so as to be visible through the window of the observatory addition. Once the alley was documented, the team moved to the courtyard, and placed the scanner at the open door to the observatory addition to capture the target through the window on the opposite the door, and tie these alley scans to the front of the buildings. Scanning progressed with the courtyard, only being delayed by the appearance of a professional photographer hired to photograph the observatory. The documentation team took this opportunity to gain access to the roof of the observatory addition, and collect data from four scan locations in an effort to collect as much data of the roofs and dome as possible (Figure 4-16). From there the east side of the observatory cottage was documented, followed by the west side of the Maria Mitchell house. With the remaining hours, the scanning team documented the caretaker's addition to the Maria Mitchell house that houses the curator's office.

With this project, a high degree of accuracy was required. Therefore, the documentation team tried to ensure that all of the pertinent areas of the interiors and exteriors were documented. Sometimes this meant that additional scans were required of areas, such as the alcove next to the chimney on the original kitchen of the Mitchell house. It was decided that scans that were about six minutes in length would be required, since they provide a density of around 5.6mm at a distance of 10 meters. Again, the Faro Focus^{3D} specifications state that it is accurate to with a few millimeters, which is very important for heritage documentation.

The documentation team made sure to load batches of scans as they were collected into Scene to ensure that no areas were left unscanned resulting in holes in the point cloud model. However, there were a few obvious areas in which the documentation team knew that they were going to not collect data. The northwestern side of the observatory dome was one such area with which the team knew they would likely not be able to collect points. Additionally some areas on the roofs of the dormitories and observatory cottage were known to have been missed, but no vantage point was available to capture the missing data.

Data management

To process the scans from this project, two main parent folders were created. One parent folder contained all of the interior scans, while the other contained all of the exterior scans. Within the interior scan cluster, additional folders were created for each floor of the structure: cellar, first floor, second floor, and attic. The exterior cluster was also split into two subfolders: a folder containing scans north of Vestal Street and a folder containing scans south of Vestal Street. The northern folder contained a cluster for the alley scans as well as a cluster for the remaining northern exterior scans. The southern folder was split into three clusters: one cluster containing the targetless scans from behind the Science Library, one containing the scans to the east of the Science Library, and the other containing scans to the west of the Science Library.

Target registration occurred throughout all of the levels of folders to ensure that a standard nomenclature was used, and that overlapping targets were identified properly in all of the scans. From there the registration process started at the lowest level of clusters, and was worked upwards from there. The scans without targets were registered using the planar surfaces of the Science Library chimney and back wall. The chimney was registered as a planar surface again in the scans in the western cluster where it was picked up by the scanner. Once all the range maps were registered in the clusters in each folder, they were then registered together in the parent folder. This process required some time to plan out and implement, but it enabled the computer to handle the data in smaller increments, allowing the computer to process quicker than if this step had not been done.

It was at this point that the multiple range maps were combined into the single point cloud. During this processing phase, the color images taken by the scanner were applied to the scans. Again, the software encountered the image error, and some of the images were disconnected from their scans, resulting in parts of the point cloud remaining black and white. Nevertheless, in this case, the interior spaces of the Mitchell House were able to retain their color, while some of the exterior scans of the courtyard on the north side of Vestal Street maintained their color through the images.

Using clipping boxes within the Scene software, large sections of the vegetation were removed so that the structures were more visible. These clipping boxes were also used to slice the interior of the Mitchell house to provide simple floor plans. These floor plans were compared with the original HABS drawings to determine how accurate the hand measurement was of areas such as the central chimney (Figure 4-17). Aerial views of the Vestal Street site were created, along with some views from the side to depict the slope of the ground along the property. Once again, the point cloud, as well as the images produced from it, is currently being brought into AutoCAD to produce line drawings of the interior of the Mitchell House. As with the other models, the representation of the site through the 3D point cloud model is not perfect because of noise captured by the scanner. Examples of noise causing phenomena in this case are passing cars, the documentation team, and individuals touring the property. These extraneous points can be further removed to produce a cleaner point cloud model.

Data archiving

The same three means of data storage were used on this project as those of the Miami Marine Stadium project as well as the Washington Street Maria Mitchell project. Since these scans were completed during the same documentation trip as the other Mitchell properties, the same little hitch in the data storage process applied to this project as well because the protocols were not followed closely. Once again, although the individual files had been saved elsewhere, the actual project file was only saved in the same location as the other project. This again encountered hard drive corruption during transport. Luckily, this project information was also salvaged from the hard drive and the data was saved by following the protocols correctly.

The same measures towards metadata and file formats used for the other two case study projects were applied to this project. Additionally, as with the Washington Street properties, in agreement with the Nantucket Maria Mitchell Association, the models and other products will be made available through the Association. Excluding of course, the model depicting the interior scans of the Maria Mitchell house for the reasons mentioned earlier. This way the selected information is accessible to all interested in the Maria Mitchell properties.

However, there is one metadata caveat that has yet to be implemented, but may still be completed in the near future. For the interior of the Maria Mitchell property, working with the curator, metadata can be attached to objects and artifacts within the building. Possible information that can be linked includes maintenance plans for the items, catalogue information, as well as any historical information on the pieces in the collection. This way the 3D point cloud model acts as a digital repository that enables better workflow and information access for the parties involved. Additionally, the models can be linked with the existing HABS documentation products that were produced by previous documentation teams.

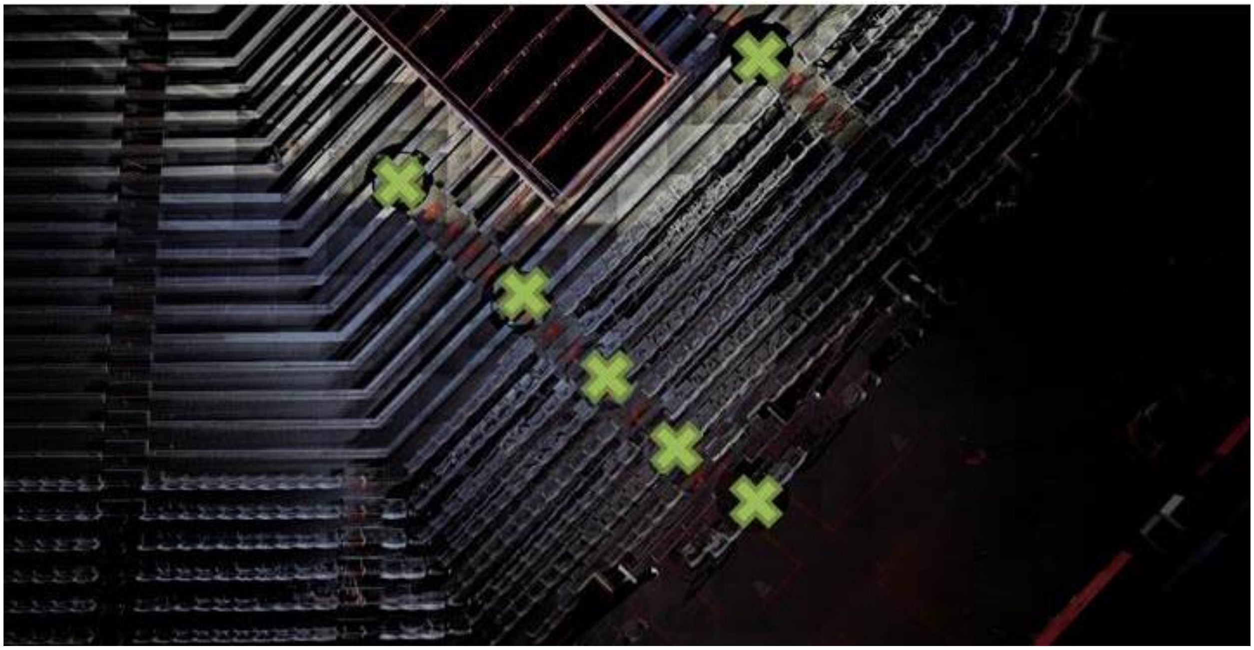


Figure 4-1. Test scans of Ben Hill Griffin Stadium. Image courtesy of Envision Heritage team.

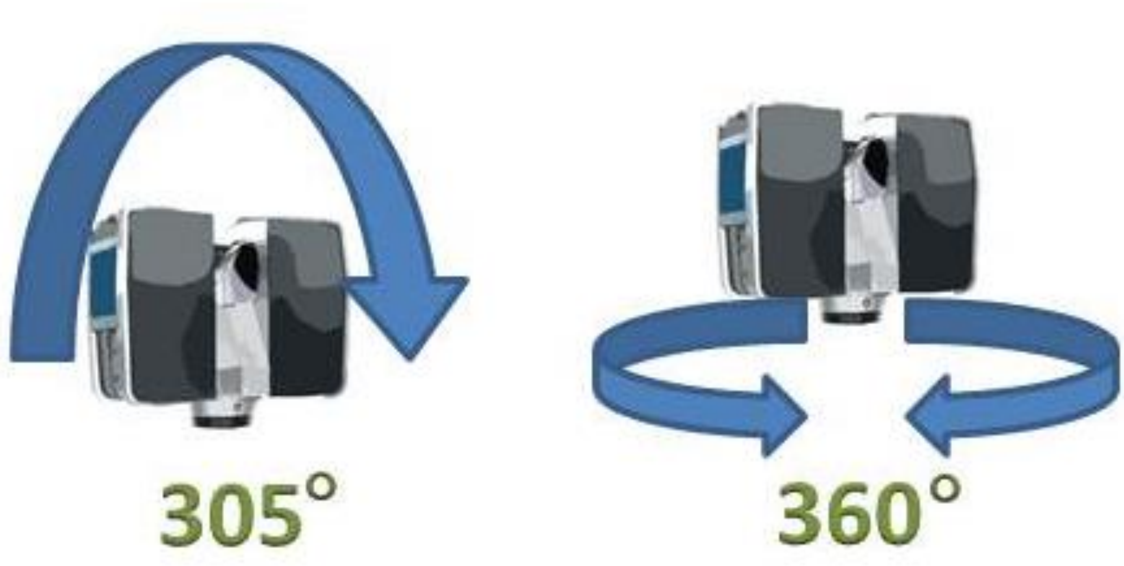


Figure 4-2. Degrees in which the laser beam is projected into the environment. Image courtesy of Envision Heritage team.

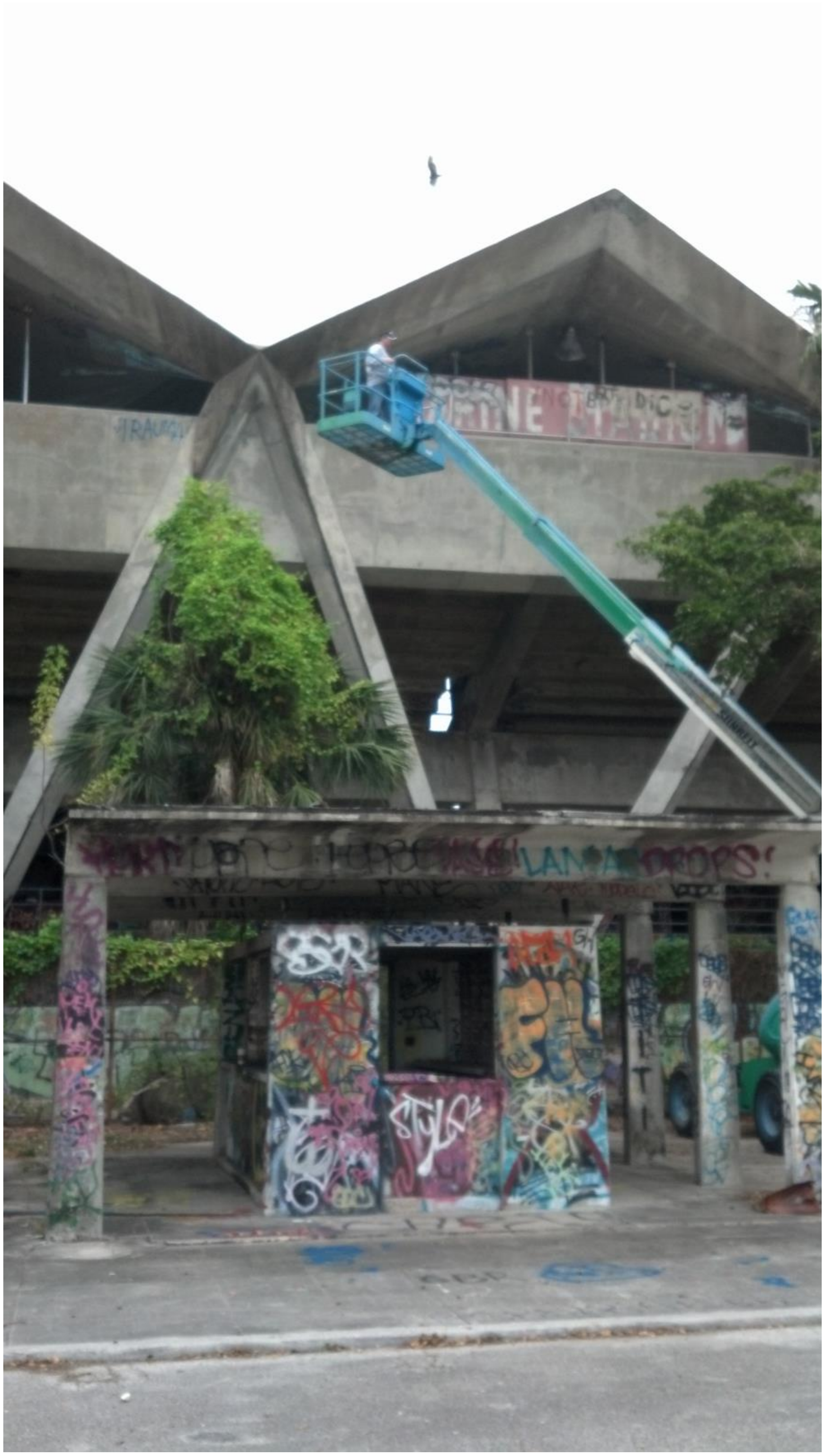


Figure 4-3. Photo of boom lift to access roof of Miami Marine Stadium. Image courtesy of Envision Heritage team.

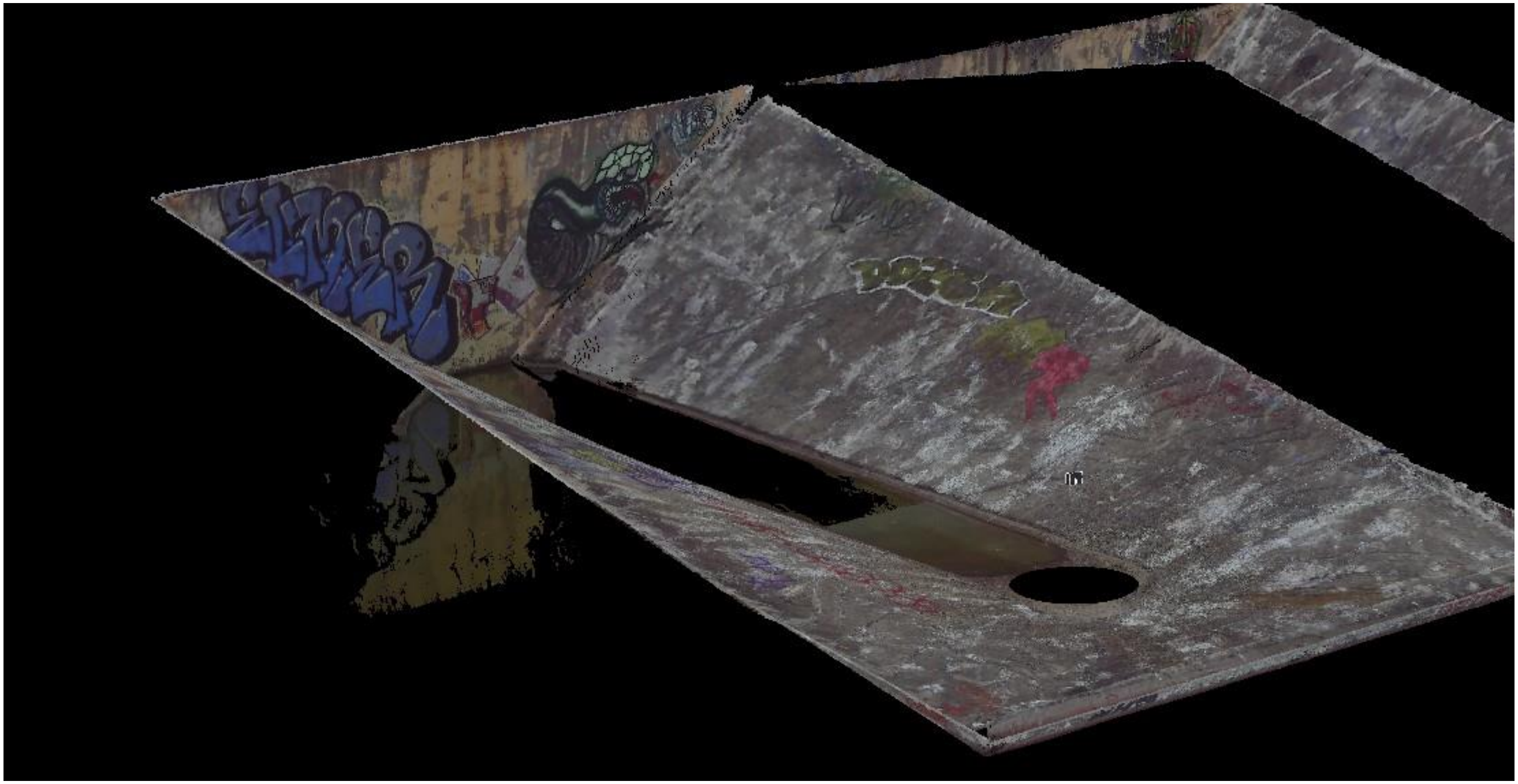
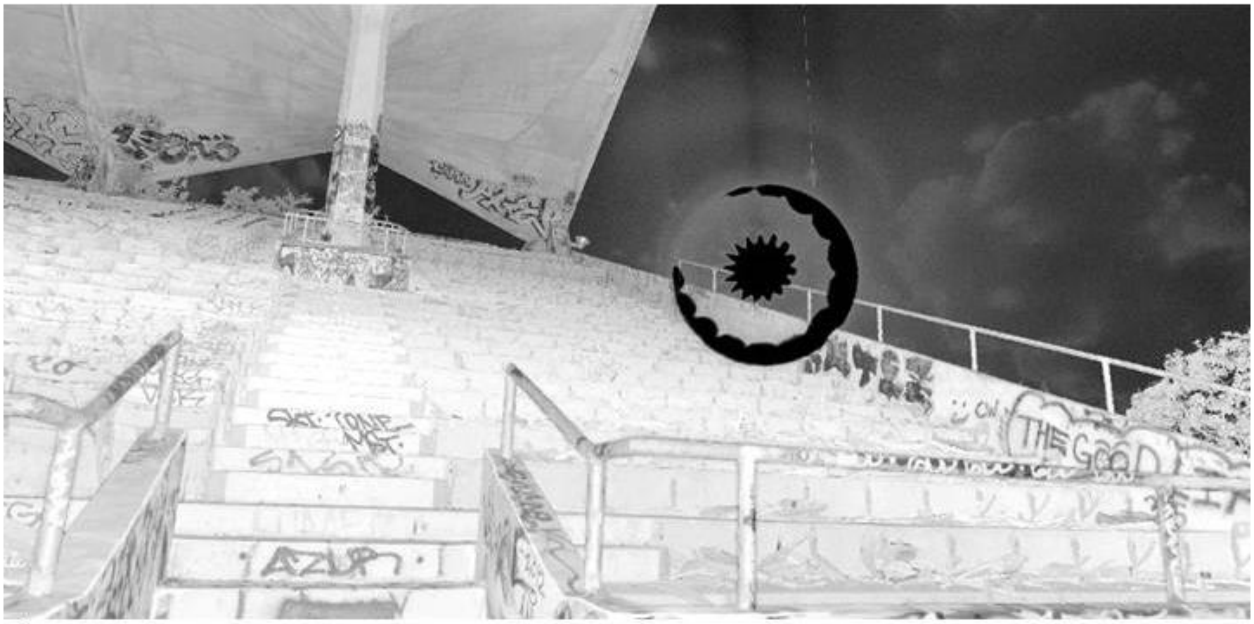


Figure 4-4. Here the colored range map shows how the water reflected the laser onto the wall, and therefore produced inaccurate points. Image courtesy of Envision Heritage team.



A

B

Figure 4-5. Images of missing scan points caused by the sun. A) Depicts the 2D uncolored representation of the scan points with the sun damage. B) Depicts the actual loss of points in the colorized range map. Images courtesy of Envision Heritage team.

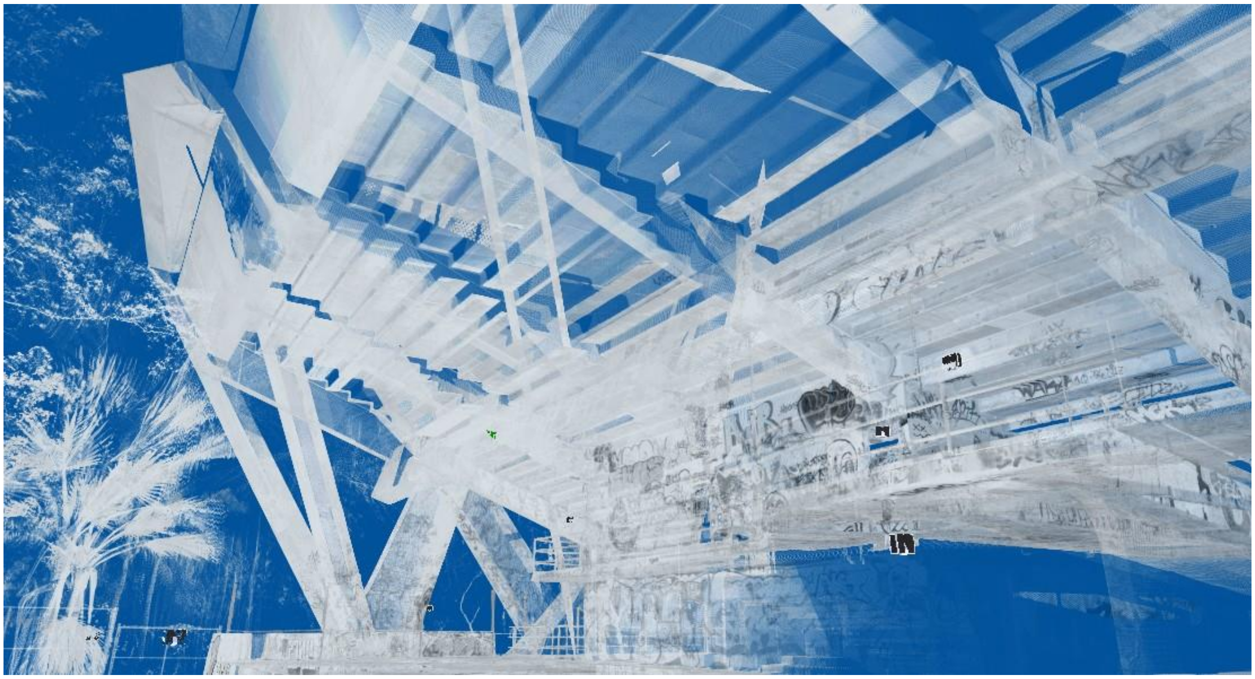


Figure 4-6. Clear view image of the concession side of Miami Marine Stadium. Image courtesy of Envision Heritage team.

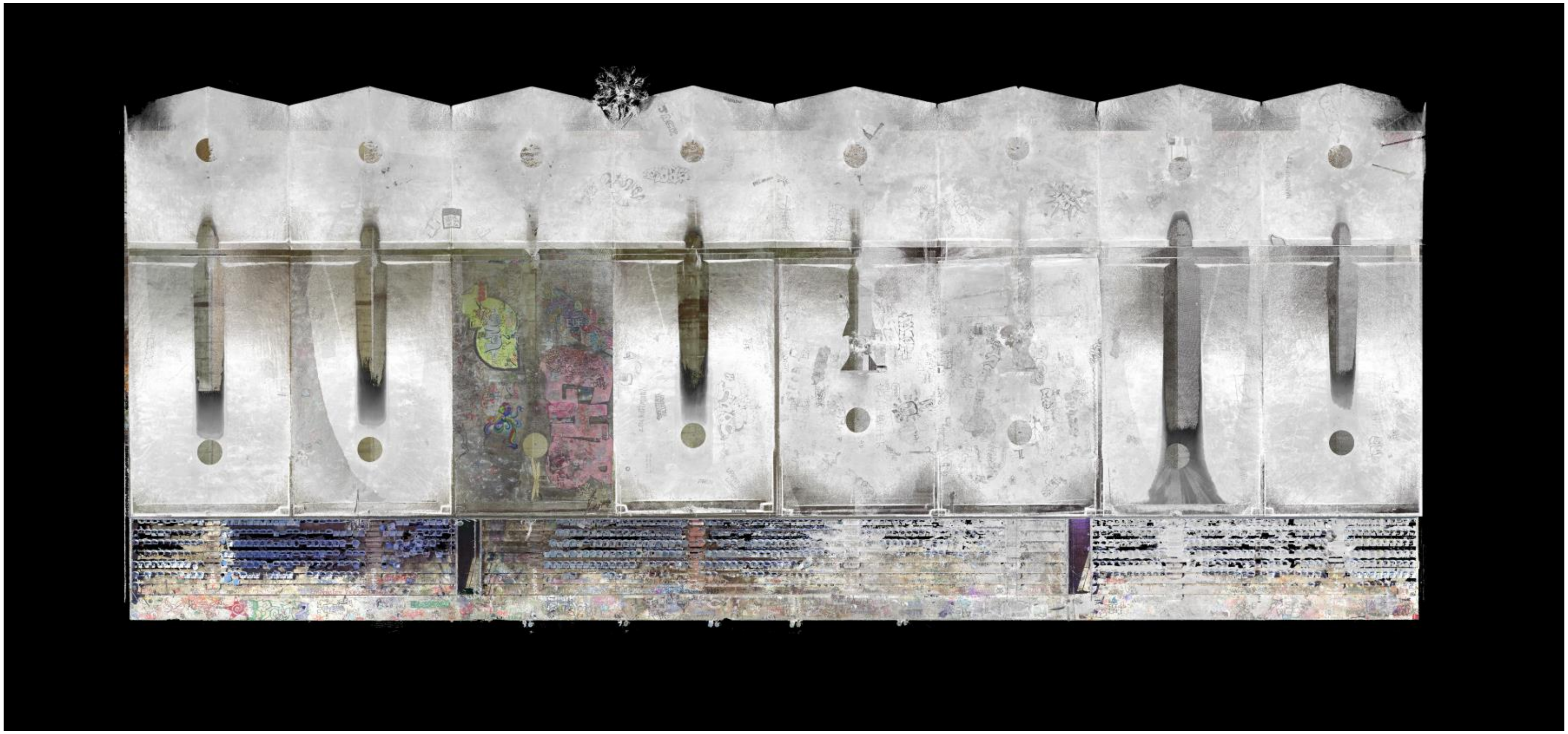


Figure 4-7. Roof plan of Miami Marine Stadium. Image courtesy of Envision Heritage team.

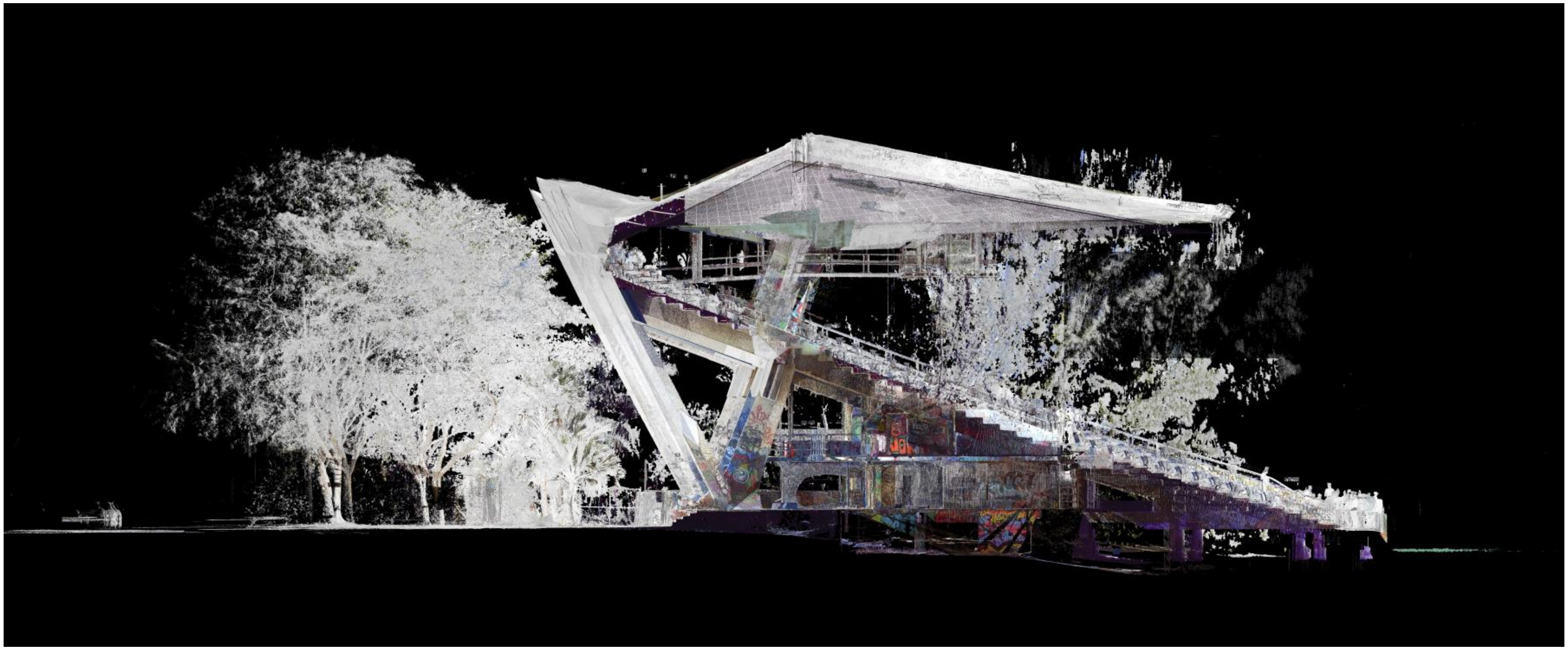


Figure 4-8. Transverse section of Miami Marine Stadium. Image courtesy of Envision Heritage team.

Figure 4-9. Sketch of Building 1 of Maria Mitchell Washington Street property. Image courtesy of Graduate Research Assistant Kara Litvinas.

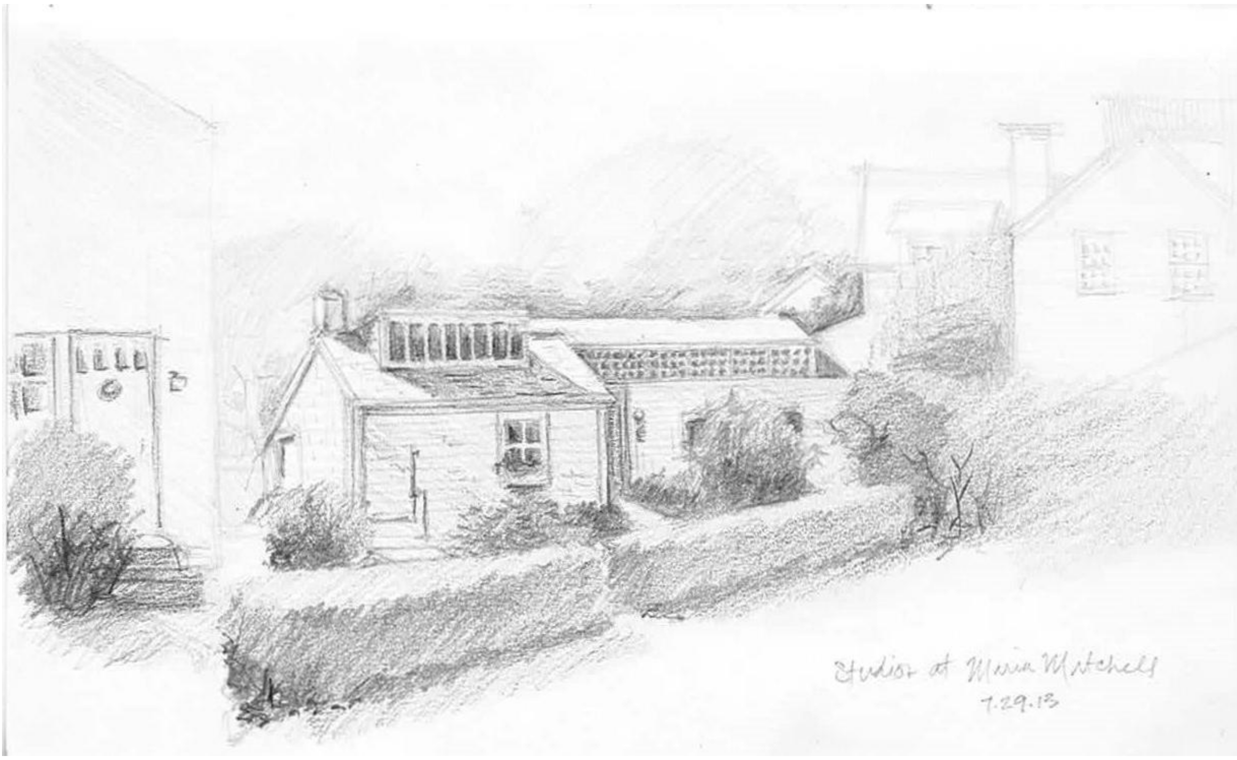


Figure 4-10. Sketch of Buildings 2-4 of the Maria Mitchell Washington Street property. Image courtesy of Graduate Research Assistant Kara Litvinas.

Figure 4-11. Clear view point cloud of Maria Mitchell Washington St. site. Scanner locations are clearly visible. Image courtesy of Envision Heritage team.

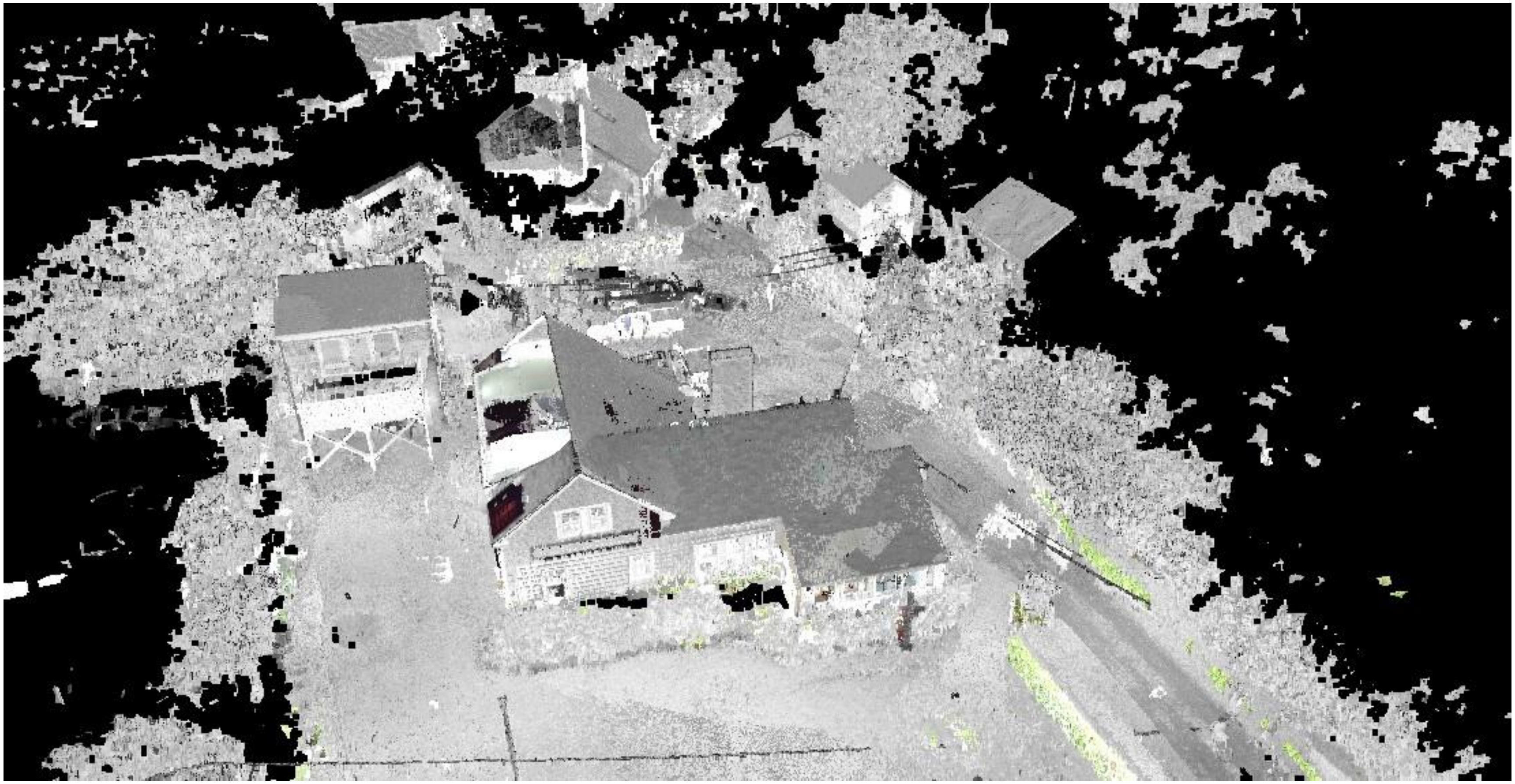


Figure 4-12. Point cloud of Maria Mitchell Washington St. site. Image courtesy of Envision Heritage team.

Figure 4-13. Site plan of Maria Mitchell Washington St. site. Image courtesy of Envision Heritage team.

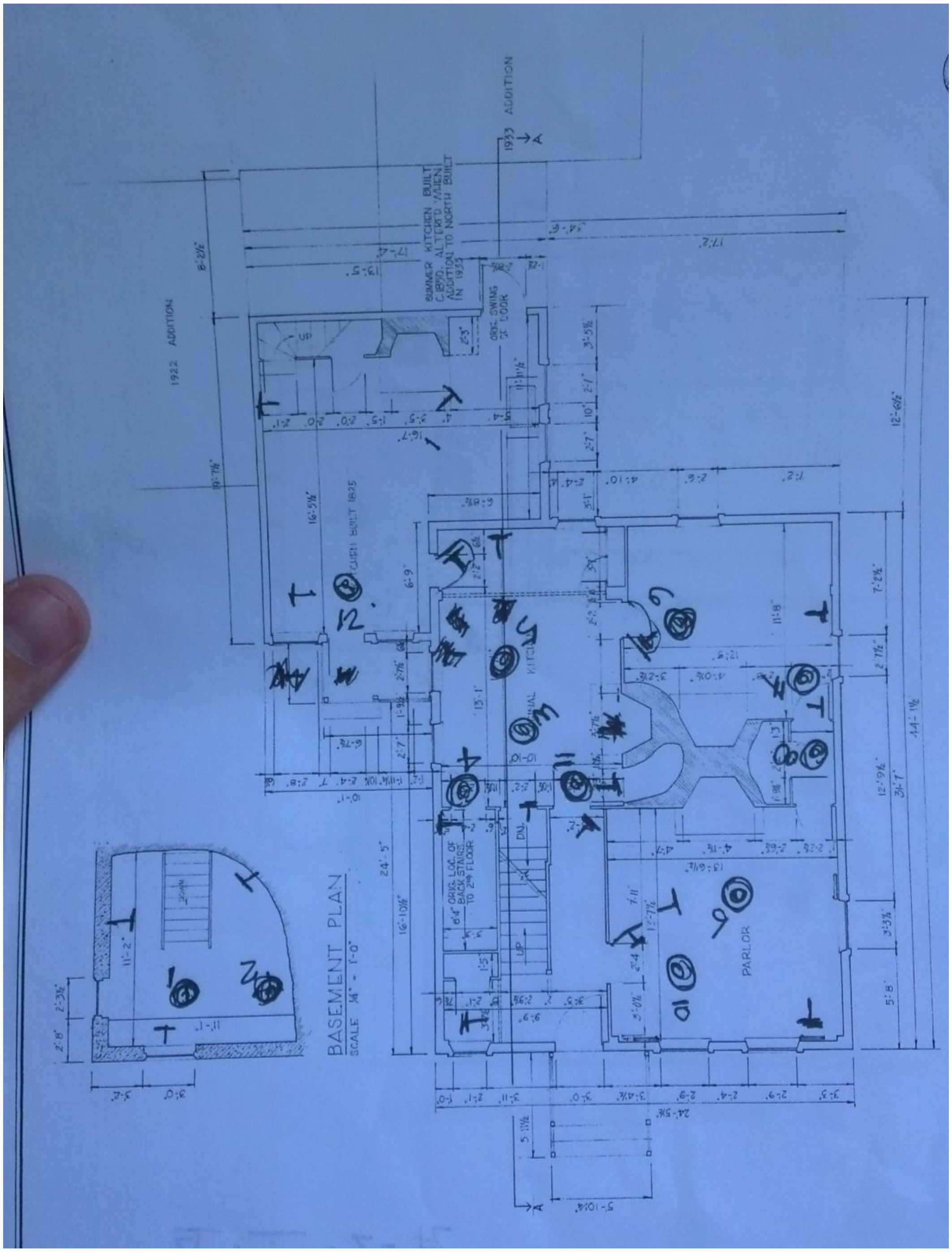


Figure 4-14. Maria Mitchell Vestal St. scan plan using HABS documents. Image courtesy of Envision Heritage team.

Figure 4-15. Documentation from the roof walk of Maria Mitchell Home. Image courtesy of Envision Heritage team.

Figure 4-16. Documentation from roof of brick observatory addition. Image courtesy of Envision Heritage team.

A

B

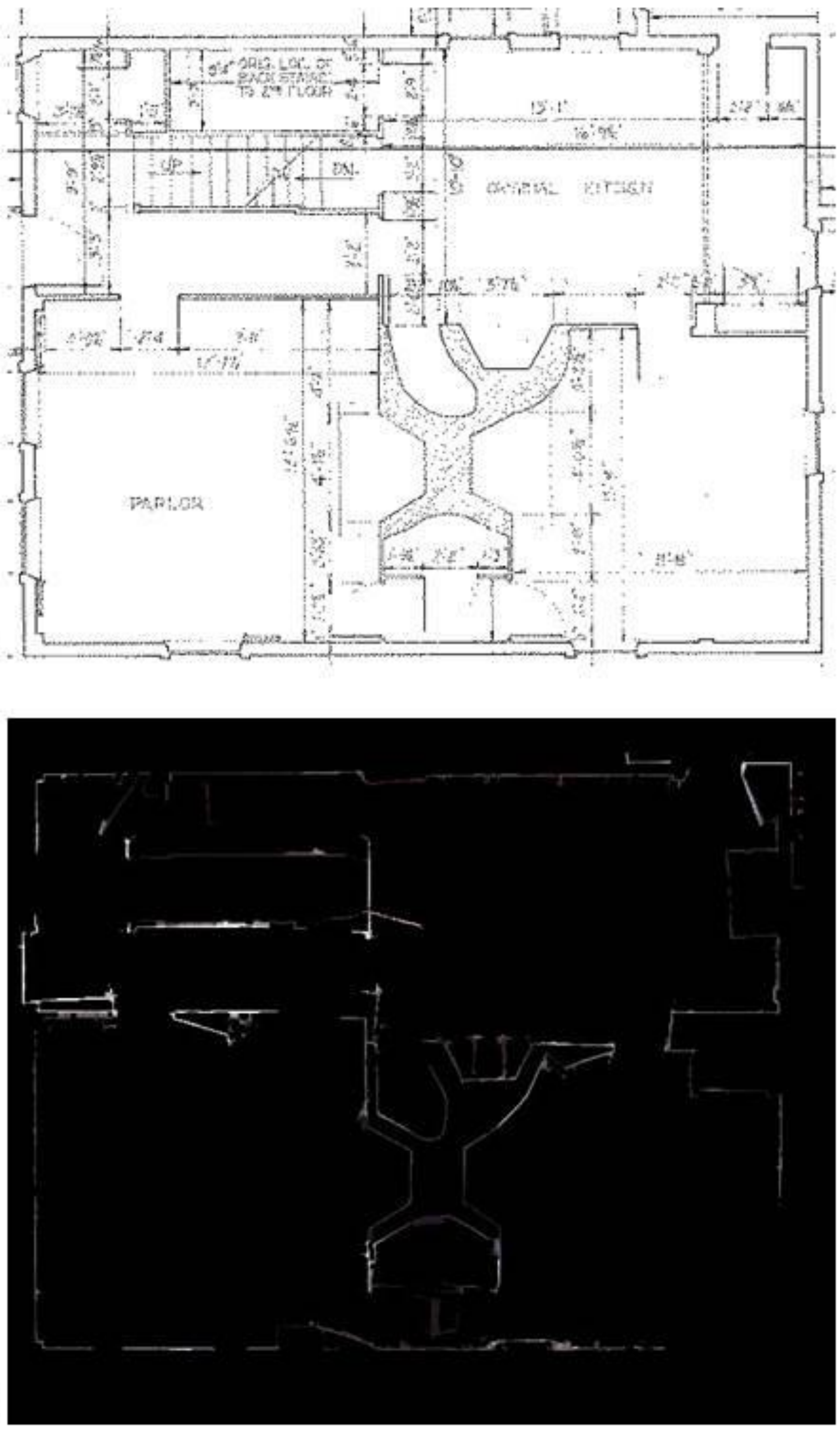


Figure 4-17. Comparison of HABS drawings and point cloud section. A) Depicts the original HABS documentation of the Mitchell House. B) Depicts a plan produced by the 3D point cloud showing that the fireplace in the original HABS was not documented as accurately as it could have been. Image A courtesy of HABS. Image B courtesy of Envision Heritage team.

CHAPTER 5
CONCLUSION

Deductions

If there is one thing that this thesis has proven to be true, it is that like cultural heritage preservation, the best practices for 3D laser scanning need to be fluid rather than static. Preservation as a field has to continually progress, because as time goes on the definition of what is historic changes as well. This progression should continue to include the acceptance of new forms and tools of documentation. Standards for these tools and forms would continue to be dynamic allowing for change as the technologies and products progress.

Not every site is going to need the same standards of preservation. Therefore, the applications and uses for 3D laser scanning will differ from site to site. Because sites of the recent past and sites from antiquity vary so greatly, the standards set forth for their digital preservation are inevitably required to be broad enough to encompass the different needs of the individual sites, while still ensuring a baseline standard. It is up to the documentation team to determine through planning and site assessments exactly what technologies and techniques are required to produce the desired level of documentation. Additionally, the documentation team has to keep in mind that the current needs may be far different from future needs that this documentation will have to fulfill. If the data acquired using 3D laser scanning is able to reach archival status, and is inevitably available to researchers in the distant future, they may find the recorded information not detailed enough. However, a balance has to be found between effectively documenting a site and accurately documenting a site. The reasoning behind this is that a one to one representation of a site in point cloud form would be ideal, but to achieve the resolution of points required for this level of detail the documentation process would be too time consuming to be an effective form of documentation.

Professor Robert Warden should be proud that preservationists have a new tool to add to their tool belt. Doubly so, when it is considered that 3D laser scanning is not the be-all and end-all tool for documenting historic sites. The case studies alone show that relying solely on one form of documentation technology is not enough to ensure that a historic site is preserved in record. Instead 3D laser scanning should be treated as another tool, one that may not be the right tool for every job, but that is invaluable to the user when the situation calls for its use. HABS, CyArk and other programs are right to encourage the use of 3D laser scanning, but so long as documentation occurs in various forms.

Additionally this research showed that consensus amongst these programs is nearly reached. This is best exemplified by the required resolution standards set forth by CyArk and English Heritage. Although the terminology describing the objects being documented varies, some standard resolution requirements are similar. From this, a nomenclature should be established that better defines the category requirements for these resolution classifications, or at least the adoption of size options presented in the English Heritage table. If they are broad enough, then documentation teams working in the field will have a better grasp of where the object being scanned falls into the resolution spectrum. However, again it is up to the documentation team to determine if the minimum baseline resolution is enough to meet the project goals.

The case studies presented in this thesis show that born digital data is prone to dangers that traditional data collection methods are not. However, there are steps that can be taken that mitigate the dangers, so long as they are properly followed. Corruption of the digital data can occur at any time after its initial capture, whether it be while the information if still in the 3D laser scanner, while the information is transferred to the processing computer, during the processing of the digital data, or in the storage formats and locations of said data. Therefore, efforts have to be made by the documentation team to ensure that the data is secure, because it will not matter what the intended life span is for E57 file format if the data is stored in such a way that leads to its corruption.

Limitations

It is important to note that there are limitations encountered in the research done for this thesis. These limitations exist in the actual hardware, the availability of documentation techniques, and the amount of time available to complete the research.

The most prominent limitation is in the hardware used to document these sites. While the scanner is a marvel for its size, speed and accuracy, the market drives producers of the technology to continually produce the next evolution of the product. For example, where the Faro Focus^{3D} is capable of accurately capturing data at a range of 150 meters, the new Faro Focus^{3D} X330 is capable of accurate point capturing at a distance of 330 meters. Additionally where the wavelength of the Focus^{3D} gets lost in sunlight, the newer X330 model uses a wavelength unaffected by sunlight. That is not to say that the research conducted would have benefited solely from an updated model, but rather that the research can only accurately assess the methodologies as they applied to case studies using this specific scanner.

Additionally, because case study sites were chosen based upon the existing equipment, they therefore produced limited results. Working from the viewpoint of case study selection without a thought to the technology to be used, more creativity would arise in the documentation process. Having the option of multiple types of scanners, be they TOF or phase shift, the documentation team would have to assess further which scanner were to be used, or where both would be used to optimized documentation. Again, with the inclusion of multiple devices with their own proprietary software, the file formats from the scans could be different. Therefore, the team would have to ensure that at least one of the programs was able to handle cross compatible file formats.

The research was also limited in that it did not use tools that were recommended in the literature review. For example, the Faro Focus3D has a built in camera, which saves the images to be opened in the proprietary software. If the CyArk recommendation had also been followed, and the site was documented with a DSLR camera, then images could have been applied to the scans that were not digitally linked to the scans before registration. It is currently unknown if images applied to scans from outside sources encounter the same software bug the documentation team encountered, but the extra layer of documentation would still be helpful rather than a hindrance.

The final limitation on this research revolves around the issue of time. A true assessment of the data archiving standards cannot be conducted in such a short time. In fact, the only way to truly assess is to continually asses the archived data as time passes. Current standards are just based off calculations and an understanding of the current trends of data capture and management. The only way to determine the success of these measures is to wait and see if they have stood the test of time, which is not a viable solution for thesis research.

Considerations

The best practices for 3D laser scanning were established in the methodology chapter based upon the documentation process experienced by professionals who work with the technology in the field. However when using these methodologies, in conjunction with the proposed best practices by the organizations mentioned in the literature review, there still existed incidences where the documentation team had to develop practices. The 3D laser scanning pipeline influenced these practices as it pertained to the case studies. However, the following practices can also be adapted to be broadly applied to any site being documented (Table 5-1).

During the planning assessment phase for these sites, the documentation team found that the project goals would often differ between the representatives of the organizations. Additionally, some organizations worked in concert with other individuals to complete projects that would benefit from the inclusion of products from the 3D laser scanning documentation. Therefore, during the planning phase, the documentation team ensured that as many individuals currently involved with the site had input on the project goals, to ensure that the documentation was effective enough for the point cloud to be useful for any possible product.

The site assessment phase for these sites also provided the opportunity for the documentation team to establish the practice of producing backup documentation plans. These documentation plans were created in an effort to ensure that the site was documented without losing any time to environmental or other conditions. Additionally, backup plans for the target planning may also be required. Differences in the weather and even the materiality of the site may exist between the site planning phase and the data gathering phase. Regrettably, this means that had the documentation plan called for the use of paper targets, taped to the structure, these targets may not stick, and result in the issue found in the Miami Marine Stadium case study.

The documentation team established a few best practices during the technology assessment phase, some of which may only be applicable to the specific scanner used for documentation of the case study sites. The first recommendation the documentation team produced was that the computers needed for the processing software should be ordered well above the specifications recommended by the owner of the proprietary software. This way, the computers will be better able to handle the processing of the scans during the data management phase. Additionally, the documentation team felt it necessary that if the scanner contains a removable battery source, then multiple batteries should be purchased for use on site. The additional batteries allow the documentation team to switch out the batteries and not lose any time from the scanning process while the battery charges. The same recommendation also occurs for the way in which the scan data is stored by the 3D laser scanner. The Faro Focus^{3D} uses a class ten memory card to store the data. The use of multiple memory cards allows data to be uploaded from the card to the computer while a separate card is in the scanner, letting documentation to continue.

The documentation team created a few additional practices that should be followed in the data gathering phase. During this phase, the documentation team had to often decide while on a site whether enough scans had been performed to accurately record the particular portion of the site. The team felt that the practice of oversampling the site was preferable to undersampling the site. Undersampling would require return trips if the 3D laser scanner did not capture enough of the site, whereas oversampling would only result in a larger file size, and thus a little more processing time. Also found to be an issue, was that while gaining access to a site for the documentation team required project planning and coordination, access was easily gained to restrictive sites by others. This access control issue was most apparent with the Miami Marine Stadium site, where individuals would scale the fence to get onto the site, and wander around the building. This meant that even in a restricted site, the documentation team had to be aware of any individuals who may get too close to the scanner or targets and produce noise in the scan. This also affected where the documentation team could go during scans. With the current technology, the options were to sit under the tripod, walk around the scanner in its blind spot the entire time, or go to an area that was out of its line of sight. However, sometimes these options were not available, and the 3D laser scanner captured the documentation team while they were ensuring data collection without interference or risk.

Nearly the single most important best practice that the documentation team recommends spans the data gathering phase and the data management phase. This recommendation is that if possible, a member of the data capture team is also a member of the data management team. Often precise field notes can take the place of this practice; however, there are times when they may not be succinct enough. Therefore, having a team member who was both on site and processing the data allows for quicker turnaround time. If other members of the processing team have questions about elements of the site, then the team member who was part of the collection team will be able to quickly answer them and work towards a solution.

The only additional practice that the documentation team recommends should be followed specifically pertains to data storage during the data archiving phase. The documentation team had the foresight to store all of the individual elements of a project. This included the important project folders for the sites. With the Faro Scene program however, files can be compacted once the project has been created. This cuts down on the file size of the project, however, it also removes all of the previous save files of the project. The documentation team saved two copies, one before compaction, and one after. This allows others to go back and view what steps had been taken at each file stage. This can be very helpful if a bug or other error occurs, and finding where the issue arose in the process is important.

Recommendations for Future Research

Data longevity is one of the topics addressed in this thesis that will require further study. However, as stated above, because of the nature of the topic, this research will have to be approached through two avenues of study. The first calls for research into other means to fortify the data in such a way that the format can be read in the future even if the original data reader is obsolete or nonexistent. The other avenue of research is long term, in which the current data storage types are analyzed at intervals of time to assess whether the files degrade over time, and at what rate this degradation occurs. This second method of research is not likely to be carried out heavily in the near future, but rather within the next decade or longer, depending on the medium the data is stored onto. Research into the different storage materials may lead to more in-depth investigation of storage types, such as CyArk's gold copy of archived data stored underground.

Cultural heritage preservation is already an interdisciplinary field, which includes experts in architecture, interior design, archaeology, and urban planning to name a few. This interdisciplinary aspect was what allowed the laser scanner technology to be adopted, and influenced by the fields mentioned in the introduction. Heritage applications for laser scanning stemmed from the intended use of the product, adapted to meet the needs of researchers in the field. This adoption and adaptation should be fostered, with research being done into other fields to ascertain ways in which existing documentation methodologies can be expanded upon for cultural heritage applications.

Additionally, this interdisciplinary expansion research should assess new technologies that are being produced for other fields of study. These new technologies can quite possibly be adopted the same way that 3D laser scanning was, providing preservationists with even more tools to use when working with cultural heritage.

Table 5-1. List of proposed practices

Phase	Proposed Practice
Planning Assessment	Determine and include all individuals in the planning phase that may have influence on the products produced.
Site Assessment	Produce backup documentation plans and target locations.
Technology Assessment	Purchase computers that are above the recommended specifications.
	Ensure proper power is available for the scanner at all times so as to not hinder the documentation process.
	Ensure that data transfer from the scanner hardware to the processing hardware does not hinder the documentation process.
Data Gathering	Oversampling is preferred to undersampling, despite the increase in processing time and file size.
	Always ensure access control and safety protocols no matter how controlled the access to the site.
	Ensure documentation without incidence by remaining proximally close to the scanner at all times.
Data Management	Ensure that members who participated in data collection are also part of the data processing team.
Data Archiving	Ensure multiple backups or versions of files exist should any issues arise.

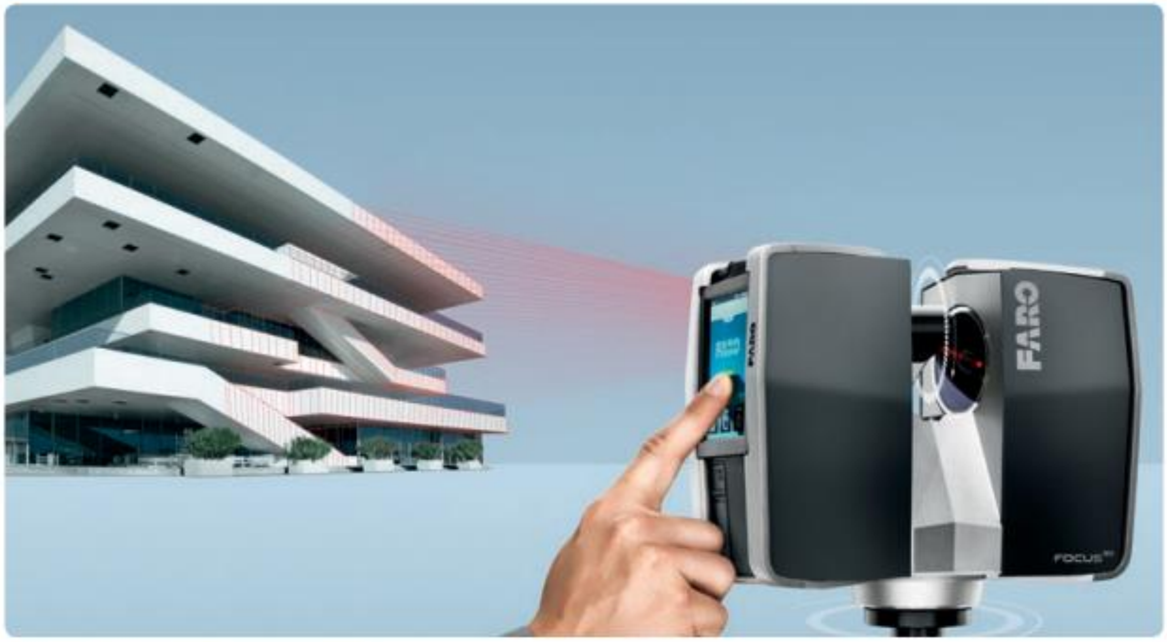
Proposed practices produced by the documentation team.

APPENDIX
FARO FOCUS^{3D} TECH SHEET

FARO Focus^{3D}
Features, Benefits & Technical Specifications

Focus^{3D}

FARO



A leap in innovation and efficiency to lower your costs

The Focus^{3D} is a high-speed 3D laser scanner for detailed measurement and documentation. With a touch operated screen to control scanning functions and parameters, the Focus^{3D} uses laser technology to produce incredibly detailed three-dimensional images of complex environments and large scale geometries in only a few minutes. The resulting image is an assembly of millions of 3D measurement points that provide an exact digital reproduction of existing conditions.

The Focus^{3D} offers the most efficient method for three-dimensional documentation of building construction, excavation volumes, façade and structural deformations, crime scenes, accident details, product geometry, factories, process plants and more. Given its minimal size and weight as well as touch interface, the Focus^{3D} is easy to work with and saves up to 50% of scan time compared to conventional scanners.

How the Focus^{3D} works

The technology behind the Focus^{3D} is simple. First, it emits a laser beam from a rotating mirror out towards the area being scanned. Then the unit distributes the laser beam at a vertical range of 305° and a horizontal range of 360°. The laser beam is then reflected back to the scanner by objects in its path. The distance to the objects defining an area is calculated as well as their relative vertical and horizontal angles. The data is captured and transmitted via WLAN for calculating precise 3D renderings.

Focus^{3D}

FARO

Features of the Focus^{3D}

Intuitive touchscreen display
Control all scanner functions with a touch interface for unparalleled ease of use and control

Small and compact
With a size of only 9.5 x 8 x 4in and a weight of just 11lbs, the Focus^{3D} is the smallest 3D scanner ever built

Integrated color camera
Photorealistic 3D color scans due to an integrated color camera featuring an automatic 70 megapixels parallax-free color overlay

High-performance battery
Integrated lithium-ion battery provides up to five hours of battery life and can be charged during operation

Data management
All data is stored on a SD card enabling easy and secure transfer to a PC. Using SCENE WebShare, images can be shared on the internet

Compass
An electronic compass is now included within the unit to associate directional data to your scans and facilitate the auto-registration process

Height Sensor (Altimeter)
Each scan now includes height information which can be used to scan different floor levels in a building. The data can then be used to differentiate the floors

Dual Axis Compensator
To minimize the number of targets needed, the dual axis compensator enables every scan to have integrated level information

WLAN (WiFi)
WLAN remote control permits you to start, stop, view or download scans at a distance

Benefits to the end user

- Portability allows user to scan complex objects and environments
- Automatic scan registration reduces pre-processing scan time
- Large scanning range reduces the number of scans per project
- Touchscreen interface makes the scanner easy for anyone to use

Benefits to the company

- Provides long term investment for future projects
- Dedicated users can act as general scanning providers within organization
- Real world environments are preserved in a virtual 3D world
- Unsurpassed cost-value proposition make every scanning project economical

FARO Focus^{3D}

www.faro.com/focus

FARO

Performance Specifications

GSA Contract Holder

Ranging Unit
Unambiguity interval: 153.49m (503.58ft)
Range Focus^{3D} 120[1]: 0.6m - 120m indoor or outdoor with low ambient light and normal incidence to a 90% reflective surface
Range Focus^{3D} 20: 0.6m - 20m at normal incidence on >10% matte reflective surface*
Measurement speed: 122,000 / 244,000 / 488,000 / 976,000 points/sec
Ranging error[2]: ±2mm

Ranging noise[3]	@10m	@10m - noise compressed[4]	@25m	@25m - noise compressed[4]
@ 90% refl.	0.6mm	0.3mm	0.95mm	0.5mm
@ 10% refl.	1.2mm	0.6mm	2.20mm	1.1mm

Color Unit
Resolution: Up to 70 megapixel color
Dynamic color feature: Automatic adaption of brightness

Deflection unit
Vertical field of view (vertical/horizontal): 305° / 360°
Step size (vertical/horizontal): 0.009° (40,960 3D pixels on 360°) / 0.009° (40,960 3D pixels on 360°)
Max. vertical scan speed: 5,820rpm or 97Hz

Laser (Optical transmitter)
Laser power (cw Ø): 20mW (Laser class 3R)
Wavelength: 905nm
Beam divergence: Typical 0.19mrad (0.011°)
Beam diameter at exit: 3.0mm, circular

Data handling and control
Data storage: SD, SDHC™, SDXC™; 32GB card included
Scanner control: Via touch-screen display
New WiFi(WLAN) access: Remote control, Scan Visualization and download are possible on mobile devices with Flash®

Multi-Sensor
Dual axis compensator: Levels each scan with an accuracy of 0.015° and a range of ±5°
Height sensor: Detects the height relative to a fixed point via an electronic barometer and adds it to the scan
Compass: Electronic compass gives the scan an orientation. A calibration feature is included.

1) Depends on ambient light, which can act as a source of noise. Bright ambient light (e.g. sunshine) may shorten the actual range of the scanner to lesser distances. In low ambient light, the range can be more than 120m for normal incidence on high-reflective surfaces. 2) Ranging error is defined as the systematic measurement error at around 10m and 25m, one sigma. 3) Ranging noise is defined as a standard deviation of values about the best-fit plane for measurement speed of 122,000 points/sec. 4) A noise-compression algorithm may be activated to average points in sets of 4 or 16, thereby compressing raw data noise by a factor of 2 or 4. Subject to change without prior notice.

Patented: US 7,430,068 B2; 7,733,544; 7,847,922 B2
*Focus^{3D} 20 not available for distributor resale

Hardware Specifications

Power supply voltage: 19V (external supply), 14.4V (internal battery)
Power consumption: 40W and 80W respectively (while battery charges)
Battery life: Up to 5 hours
Ambient temperature: 5° - 40°C
Humidity: Non-condensing
Cable connector: Located in scanner mount
Weight: 5.0kg
Size: 240x200x100mm^3
Maintenance calibration: Annual
Parallax-free: Yes

For more information call 800.736.0234
or visit www.faro.com/focus

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BIOGRAPHICAL SKETCH

Brian Shea was born in Hialeah, Florida and lived most of his life in Broward County. He received his Associate in Arts in architecture in 2006 from Broward Community College (now Broward College). In 2010, he received his Bachelor of Arts in history, with a minor in urban and regional planning. It was in one of the classes needed for the minor, that Brian got his taste for historic preservation. In 2011, Brian started concurrent degrees in an effort to receive both a Master of Historic Preservation and a Master of Arts in urban and regional planning. Brian graduated in the fall of 2013 with his Master of Historic Preservation, and graduated in the spring of 2014 with his Master of Arts in urban and regional planning. Brian plans to continue pursuing his dual interests by finding a career that incorporates both planning and preservation.