Documentation for the Conservation of Built Heritage: Analysis of
Recording Methodologies

by

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Abstract

The concept of resource management in relation to cultural heritage relies on the keeping of records as its fundamental core. A consistent approach to record keeping is necessary for the further analysis of any heritage conservation project, because without these baseline records, no direction can be taken. This Master's thesis is focused on exploring digital heritage recording techniques and data processing workflows to aid in the conservation of built heritage sites. Four sites of varying scale, scope of work, and heritage value have been chosen to illustrate how heritage documentation practices are approached from local, national, and international perspectives, and the results that can be obtained from each. The Log Farm in Nepean, Ontario, Prince of Wales Fort in Churchill, Manitoba, and QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen in Luxor, Egypt, serve as case studies to further examine heritage recording in practice.

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Glossary

Below is a glossary of key terms that will be used throughout the duration of this thesis. The definitions of some of these terms will be repeated throughout this work to show an emphasis on their importance to the subject matter.

Character-defining Element: Characteristics of an historic place, whether of tangible or intangible nature, that contribute to gaining an understanding of the values of that site that must be conserved

Conservation: “All actions or processes that are aimed at safeguarding the character-defining elements of an historic place so as to retain its heritage value and extend its physical life. This may involve *Preservation*, *Rehabilitation*, *Restoration*, or a combination of these actions or processes.”¹

Cultural Heritage: “Refers to tangible and intangible evidence of human activity including artefacts, monuments, groups of buildings and sites of heritage value, constituting the historic or built environment.”²

Documentation: “The already existing stock of information. As an activity, it stands for the systematic collection and archiving of records in order to preserve them for future reference.”³

Electronic Distance Measuring (EDM): Component of the total station instrument that measures distances.⁴

¹ Parks Canada, *Standards and Guidelines for the Conservation of Historic Places in Canada: A Federal, Provincial and Territorial Collaboration*. (Ottawa: Parks Canada, 2010), 17.

² Historic England, “3D Laser Scanning for Heritage | Historic England,” October 31, 2011, 19, <https://historicengland.org.uk/images-books/publications/3d-laser-scanning-heritage2/>.

³ Robin Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles* (Shaftesbury, Dorset, UK ; Michigan, USA: Donhead Pub, 2011), 119.

⁴ Sathesh Gopi, R Sathikumar, and N Madhu, *Advanced Surveying: Total Station, GIS and Remote Sensing* (New Delhi: Pearson Education : Dorling Kindersley (India), 2007), chap. 8, <http://proquest.safaribooksonline.com/?fpi=9789332501430>.

Ground Sample Distance (GSD): The relationship between the size of one pixel on the image, and how that corresponds to a set measurement on the object that is being surveying.

Ground Control Point (GCP): “A point of the object which is illustrated in the image while at the same time its 3D coordinates (X , Y , Z) are known, either in a local reference system or in a global reference system.”⁵

Heritage information: “The integrated activities of recording, documentation, and information management.”⁶

Heritage recording: “The graphic and/or photographic capturing of information describing the physical configuration, evolution, and condition of a heritage place at known points in time.”⁷

Heritage Value: “The aesthetic, historic, scientific, cultural, social or spiritual importance or significance for past, present and future generations. The heritage value of an historic place is embodied in its character-defining materials, forms, location, spatial configurations, uses and cultural associations or meanings.”⁸

Information management: “The process of finding, cataloguing, storing, and sharing information by making it accessible to potential users now and in the future.”⁹

Point Cloud: A series of points visually representing the object or resource that also contain geometric coordinates for measurement applications

⁵ Efstratios Stylianidis, Andreas Georgopoulos, and Fabio Remondino, “Chapter 5- Basics of Image-Based Modelling Techniques in Cultural Heritage 3D Recording,” in *3D Recording, Documentation and Management of Cultural Heritage* (Dunbeath: Whittles Publishing, 2016), 268, <http://site.ebrary.com/lib/oculcarleton/docDetail.action?docID=11276440>.

⁶ Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles*, 119.

⁷ Ibid.

⁸ Parks Canada, *Standards and Guidelines for the Conservation of Historic Places in Canada*, 5.

⁹ Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles*, 119.

Point Intensity: “A qualitative measure of the relative strength of the power of the received signal” and involves characteristics such as object reflectivity and surface roughness.¹⁰

Preservation: “The action or process of protecting, maintaining, and/or stabilizing the existing materials, form, and integrity of an *historic place*, or of an individual component, while protecting its *heritage value*.”¹¹

Primitive: Best fit shapes (planes, spheres, cylinders) applied to the object of interest depending on its geometry. They are modeled by a triangular mesh.¹²

Raking light: A technique in which surfaces of interest are “illuminated from one side only, at an oblique angle in relation to its surface” in order to visually display the surface textures.¹³

Recording: “The acquisition of new information deriving from all activities on a heritage asset, including heritage recording, research and investigation, conservation, use and management, and maintenance and monitoring.”¹⁴

Rehabilitation: “The action or process of making possible a continuing or compatible contemporary use of an *historic place*, or an individual component, while protecting its *heritage value*.”¹⁵

Restoration: “The action or process of accurately revealing, recovering or representing the state of an *historic place*, or of an individual component, as it appeared at a particular period in its history, while protecting its *heritage value*.”¹⁶

¹⁰ C. Crespo et al., “Damage Detection on Historical Buildings Using Unsupervised Classification Techniques,” *International Archives of Photogrammetry*, 2010, 184.

¹¹ Parks Canada, *Standards and Guidelines for the Conservation of Historic Places in Canada*, 17.

¹² Yueqian Shen, Roderik Lindenbergh, and Jinhu Wang, “Change Analysis in Structural Laser Scanning Point Clouds: The Baseline Method,” *Sensors* 17, no. 1 (December 24, 2016): 10, doi:10.3390/s17010026.

¹³ NationalGallery.org.uk, “Raking Light,” accessed July 20, 2017, <http://www.nationalgallery.org.uk/paintings/glossary/raking-light>.

¹⁴ Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles*, 120.

¹⁵ Parks Canada, *Standards and Guidelines for the Conservation of Historic Places in Canada*, 17.

¹⁶ Ibid.

Special Flight Operations Certificate (SFOC): The document allowing the use of UAVs for any application other than flying for fun and pleasure.¹⁷

Structure from Motion (SfM): A photogrammetric algorithm that uses a large number of photographs, to perform a bundle adjustment of the camera rays in each image. The adjustment also calculates the camera location (with respect to the other images) and internal camera geometry (camera calibration).¹⁸

¹⁷ Civil Aviation Government of Canada; Transport Canada; Safety and Security Group, “Flying Your Drone Safely and Legally,” June 7, 2016, <http://www.tc.gc.ca/eng/civilaviation/opssvs/flying-drone-safely-legally.html>.

¹⁸ Stylianidis, Georgopoulos, and Remondino, “Chapter 5- Basics of Image-Based Modelling Techniques in Cultural Heritage 3D Recording,” 273.

Phase 1: Setting the Stage

Chapter 1: Introduction

Record keeping is an essential practice because it catalogues the past and serves as a tool to better plan for the future. Without these accounts, whether they be of intangible nature by passing down stories and memories of places deemed important, or tangible photographs of specific sites of interest, records act as page-markers in the book of life. They have the ability to metaphorically preserve a moment in time for future audiences to understand and experience.

The concept of resource management in relation to the conservation of cultural heritage relies on the keeping of records as a fundamental activity. A consistent approach to record keeping is necessary for the further analysis of any project because no new direction can be taken without baseline information. Therefore, it can be stated that documentation is at the root of cultural heritage conservation practices.

The interest in cultural heritage documentation in this research work is in relation to its conservation and how proper documentation protocols and information gathering can aid in allowing for historic sites to be experienced by future generations. As stated in *The Standards and Guidelines for the Conservation of Historic Places in Canada*, conservation is defined as “all actions or processes that are aimed at safeguarding the character-defining elements of an historic place so as to retain its heritage value and extend its physical life.”¹⁹ This concept of safeguarding values is the underlying goal of any documentation practice. Hassani reinforces this notion, saying “the fundamental need of any conservation project is understanding the object and gathering data about its physical condition prior to any action and intervention that might change the object.”²⁰

¹⁹ Parks Canada, *Standards and Guidelines for the Conservation of Historic Places in Canada*, 17.

²⁰ F. Hassani, “Documentation of Cultural Heritage; Techniques, Potentials, and Constraints,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5-W7

According to Letellier et al., the meaning of documentation is “the systematic collection of information and archiving of records in order to preserve them for future reference.”²¹ This relates back to the conservation definition specifically in relation to extending the physical life of the historic place. The documentation of cultural heritage resources has evolved greatly over the 21st century, and will continue to evolve as long as technological advancements are made. By moving from hand recording techniques to digital approaches like digital photography and laser scanning, the ways in which we have documented and will continue to document sites will also continue to advance.

This thesis will primarily focus on data gathering processes and data collection workflows in the realm of digital heritage documentation, specifically in relation to the conservation of built heritage. This work describes the decision making involved in using digital recording techniques to document four historic places of varying heritage designations; The Log Farm in Nepean, Ontario, is representative of a site that exhibits local heritage values; Prince of Wales Fort in Churchill, Manitoba, is a National Historic Site of Canada; and QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen in the Valley of the Queens and Kings in Luxor, Egypt, are illustrative of sites that have “outstanding universal value” as they are located within Ancient Thebes with its Necropolis— a UNESCO World Heritage site.²²

Heritage Engineering

Before delving into the research itself, it is integral to discuss the background factors that contributed to this process, and how exactly the gaps were identified. One of the fundamental

(25th International CIPA Symposium 2015, 31 August – 4 September 2015, Taipei, Taiwan, Copernicus GmbH, 2015), 207, doi:10.5194/isprsarchives-XL-5-W7-207-2015.

²¹ Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles*, 119.

²² UNESCO World Heritage Centre, “The Criteria for Selection,” *UNESCO World Heritage Centre*, accessed July 9, 2017, <http://whc.unesco.org/en/criteria/>.

aspects of this research is its contribution to the emerging field of heritage engineering. The NSERC Create Heritage Engineering program was established in 2015 by Carleton University. The program itself has students from Carleton University, Université de Montréal, and Université du Québec à Montréal.

The program helps fund research in the emerging field of heritage engineering because of the huge demand for young professionals to help in the conservation of Canada's aging building stock; currently, there are "more than 128,000 properties in Canada that may require intervention by heritage rehabilitation specialists."²³ The program involves "research, training and internship" opportunities for the students.²⁴ There are a few principles of the CREATE Heritage Engineering program that are taken from the *Guidelines for Education and Training in the Conservation of Monuments, Ensembles and Sites*, adopted by ICOMOS in 1993.²⁵ Although a more extensive analysis of relevant charters and texts can be found in Chapter 2, a brief analysis of this particular guideline is included in this section due to its relevance to the subject material.

Guideline 7 speaks about the interdisciplinary nature of conservation work, which is a key characteristic of the CREATE program.²⁶ Students are from disciplines in civil, mechanical, and aerospace engineering, as well as architecture and Canadian and Indigenous Studies. The program encourages students to engage with their fellow grant recipients to learn more about how each discipline approaches heritage conservation. The study term is supplemented with both in-house and international workshops, helping to further the conversation about conservation. Guideline 12

²³ NSERC CREATE Heritage Engineering, "What Is Heritage Engineering?," accessed July 16, 2017, <https://carleton.ca/heritageengineering/what-is-heritage-engineering/>.

²⁴ NSERC CREATE Heritage Engineering, "NSERC Create Heritage Engineering - Carleton University," accessed July 2, 2017, <https://carleton.ca/heritageengineering/>.

²⁵ ICOMOS, "Guidelines for Education and Training in the Conservation of Monuments, Ensembles and Sites (1993)," 1993, <http://www.icomos.org/en/charters-and-texts/179-articles-en-francais/ressources/charters-and-standards/187-guidelines-for-education-and-training-in-the-conservation-of-monuments-ensembles-and-sites>.

²⁶ Ibid.

discusses education and training in the field of heritage conservation with respect to encouraging hands-on training.²⁷ This training aspect is a fundamental part of the CREATE Heritage Engineering program through its internship opportunities. Industry supporters provide students with the chance to gain an understanding of how heritage oriented projects are undertaken in the workplace. Heritage engineering has been established to encompass three different tracks of research:

- Building Digitalization: “Developing techniques for capturing or mapping detailed physical characteristics of historic structures.”²⁸
- Building Sustainability Simulation: “Focus on computer-assisted building simulation to assess the impact of design, rehabilitation and retrofit options on heritage structures.”²⁹
- Building Rehabilitation: “Researchers develop innovative approaches for the timely identification of decay, deterioration and mitigation of defects, to help prevent major consequential damage”³⁰

Therefore, from an understanding of the main goals and objectives of the three research tracks, as well as what my own research is contributing, a formal definition of Heritage Engineering has been compiled to provide context to this work, and the works of future students.

Since the term ‘Heritage Engineering’ has not been officially codified, this author defines it as:

²⁷ Ibid.

²⁸ NSERC CREATE Heritage Engineering, “Building Digitalization,” accessed July 2, 2017, <https://carleton.ca/heritageengineering/research-tracks/building-digitalization/>.

²⁹ NSERC CREATE Heritage Engineering, “Building Sustainability Simulation,” accessed July 2, 2017, <https://carleton.ca/heritageengineering/research-tracks/building-sustainability-simulation/>.

³⁰ NSERC CREATE Heritage Engineering, “Building Rehabilitation,” accessed July 2, 2017, <https://carleton.ca/heritageengineering/research-tracks/building-rehabilitation/>.

The study of approaches, methodologies, and techniques used in the conservation of historic places.

The remainder of this thesis will have an eye towards this formal definition to ensure that the contributions made are within the realm of this field. My research is part of the ‘Building Digitalization’ stream, specifically looking at exploring ways to capture information about historic places using digital recording technologies that can be used for posterity record keeping to help aid in future interventions.

Research Questions and Problem Statement

The guiding research questions were first identified during the inaugural NSERC Create Heritage Forum in October 2015. The following were identified as relevant to the building digitalization stream upon which this thesis has been based:

- 1) How can products from digital documentation recording processes (point clouds, orthophotos, and measured drawings) be used for further analysis, i.e. structural engineering or monitoring strategies?³¹
- 2) What is the role of Unmanned Aerial Vehicles (UAVs) in cultural heritage documentation?³²
- 3) How can monitoring systems be used to understand the behavior before, during and after interventions?³³
- 4) How can Building Information Modelling (BIM) be incorporated into heritage conservation projects?³⁴
- 5) How can software be adapted for heritage conservation applications?³⁵
- 6) How can the collected information be disseminated so it can be shared effectively with, and accessed by other practitioners in the field or the general public?

³¹ Alex Federman et al., “NSERC CREATE Heritage Engineering Forum- Conference Proceedings” (Carleton University, Ottawa, Ontario, November 6, 2015).

³² Ibid.

³³ Ibid.

³⁴ Ibid.

³⁵ Ibid.

Not all of these gaps were examined for each case study. However, they have all been examined throughout this research. Therefore, based off of the gaps above the final problem statement can be written as:

There is a need for the optimization of recording methodologies for the generation of outcomes useful to the heritage engineering community, while focusing on the ability to easily disseminate that information.

From a broader sense, the overall organization of the thesis can be seen as:

- Recording Techniques: Gaps 1 and 2
- Information Interpretation: Gaps 3, 4, and 5
- Information Dissemination: Gap 6

The optimization of recording methodologies relates to the recording techniques stream, whereby research into digital recording techniques has been examined and tested. The specific meaning of optimization in this work is in regards to understanding the benefits and limitations of the digital recording techniques and using them in such a way as to get the best results possible based on the constraints of each case study.

Outcomes useful to the heritage engineering community leads into the information interpreting stage, in which current literature was examined in order to understand trends in the documentation field as to how the collected information can be used for practical purposes. The term ‘useful outcomes’ has various meanings depending on the case study site of interest; for the Log Farm, these outcomes consist of a values-based approach in order to document the site for posterity record keeping; ‘useful outcomes’ would be in relation to monitoring strategies of Prince of Wales Fort because of the effects of climate change; understanding the existing condition of QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen would be considered the outcomes for these case study sites.

The term ‘disseminate’ represents investigation to determine ways to be able to easily share this collected and interpreted information with the public realm in such a way that can be readily accessed if future conservation work is required. The way in which the three streams (recording techniques, information interpretation, and information dissemination) are organized in this thesis is shown in the table below:

Table 1.1: Summary of approaches for analysis of the case study sites

	The Log Farm	Prince of Wales Fort	QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen
Recording Techniques	Photogrammetry and Laser Scanning	UAV Photogrammetry	Photogrammetry and Laser Scanning
Information Interpretation	Building Information Modelling (BIM)	Orthophotos and Multi-temporal deformation analysis	Virtual reality
Information Dissemination	BIM and potentially the CDMICA initiative	Open source software	Virtual reality

Thesis Organization

This work is divided into three phases; Phase 1: Setting the Stage; Phase 2: Literature Review; and Phase 3: Documentation in Practice.

Phase 1 includes Chapter 1, which is an introduction to the topic of Heritage Engineering, as well as an overview of the problem statement and the gaps that will be analyzed in this research.

Phase 2 is the literature review, which in turn can be split up into four chapters; Chapter 2 discusses International Doctrinal Principles and Organizations about heritage documentation and recording practices; Chapter 3 delves into documentation references and programs, such as those created by Parks Canada, the US National Park Service (NPS) and Historic England; Chapter 4 discusses the digital recording techniques; and Chapter 5 speaks about diagnosis of data for conservation, specifically in regards to generated outcomes from the digital recording techniques.

Phase 3 covers documentation in practice and how the gaps were studied in each of the case study sites; Chapter 6 contains information about the research methodologies guiding the case study analysis; Chapter 7 talks about The Log Farm case study; Chapter 8 focuses on Prince of Wales Fort; and Chapter 9 covers the work in Egypt at QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen.

Following Phase 3, Chapter 10 details lessons learned from each of the case studies in relation to how the research gaps were answered, as well as a comparison of the recording strategies and deliverables. Chapter 11 contains concluding remarks about this research process, and further research that may be conducted based off of the results garnered through this work.

Phase Two: Literature Review

Chapter 2: International Conservation Organizations and Doctrinal Principles

In the conservation of cultural heritage, key ‘doctrine’ guide the work of practitioners. These international documents were published by the International Council of Monuments and Sites (ICOMOS), a “global non-governmental organization associated with UNESCO. Its mission is to promote the conservation, protection, use and enhancement of monuments, building complexes and sites.”³⁶ They were published in order to provide a uniform approach to conservation practice. The importance of ICOMOS is that it is an advisory body of the World Heritage Committee; it helps provide the World Heritage Committee with evaluations of historic places that are vying to be prescribed on the World Heritage List.³⁷

ICOMOS is an international body and has national committees across the globe that are responsible for looking after the interest of the organization in the particular country. It is also composed of a number of International Scientific Committees (ISCs). According to the *Eger-Xi'an Principles for The International [Scientific] Committees of ICOMOS*, these committees help to “gather, study and disseminate information concerning principles, techniques and policies related to heritage protection.”³⁸ Among those ISCs, the most applicable to this research is CIPA (Comité International de la Photogrammétrie Architecturale), most commonly referred to as CIPA Heritage Documentation.³⁹ As the name indicates, it is the body responsible for research into heritage

³⁶ ICOMOS, “ICOMOS Mission - International Council on Monuments and Sites,” accessed June 11, 2017, <http://www.icomos.org/en/about-the-centre/icomos-mission?showall=1&limitstart=>.

³⁷ UNESCO World Heritage Centre, “Advisory Bodies,” *UNESCO World Heritage Centre*, accessed February 7, 2017, <http://whc.unesco.org/en/advisorybodies/>.

³⁸ ICOMOS, “Eger-Xi'an Principles for The International [Scientific] Committees of ICOMOS- Quebec City ICOMOS General Assembly,” July 2008.

³⁹ The International Committee for Documentation of Cultural Heritage (CIPA), “The International Committee for Documentation of Cultural Heritage (CIPA) – CIPA’s Website,” accessed July 4, 2017, <http://cipa.icomos.org/>.

documentation techniques and practices. Additionally, the theme of the 26th biennial CIPA Symposium, taking place in Ottawa, Canada, from August-September 2017, is *Digital Workflows for Heritage Conservation*. This theme, along with the gaps mentioned in Chapter 1, helped to provide the inspiration behind this research.

All of the workflows and methodologies developed for the documentation of the case study sites examined in this thesis stem from these ICOMOS charters. They will be analyzed with an eye towards the concept of cultural resource documentation, and not how they have impacted the conservation field as a whole.

The ‘doctrine’ that will be discussed include:

1. The Athens Charter for the Restoration of Historic Monuments – 1931
2. International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter –1964)
3. The Burra Charter – 1979–2013
4. ICOMOS Principles for the Recording of Monuments, Groups of Buildings and Sites – 1996

1) The Athens Charter for the Restoration of Historic Monuments–1931

The Athens Charter, was adopted at the First International Congress of Architects and Technicians of Historic Monuments in 1931.⁴⁰ This charter is the first to mention the need for documentation of historic monuments. Although an analysis of conservation terminology is not a key focus of this research, it is important to include commentary about the distinction of how this

⁴⁰ ICOMOS, “The Athens Charter for the Restoration of Historic Monuments - 1931 - International Council on Monuments and Sites,” accessed June 11, 2017, <http://www.icomos.org/en/charters-and-texts/179-articles-en-francais/ressources/charters-and-standards/167-the-athens-charter-for-the-restoration-of-historic-monuments>.

charter focused on the documentation of physical objects, and not the more well-rounded approach that is taken today that encompasses natural and intangible heritage resources.

The beginning of the Charter describes seven main resolutions with respect to the act of restoring historic monuments. Though none of them contain the word ‘documentation’ explicitly, three resolutions contain principles of current documentation practice:

“1. International organizations for Restoration on operational and advisory levels are to be established.”⁴¹

“2. Proposed Restoration projects are to be subjected to knowledgeable criticism to prevent mistakes which will cause loss of character and historical values to the structures.”⁴²

“3. Problems of preservation of historic sites are to be solved by legislation at national level for all countries.”⁴³

The international organizations aspect relates to documentation because it is these national bodies that help to regulate the profession, thereby establishing standards for how work should be conducted. The restoration criticism relates because this criticism should be properly noted and documented for other practitioners to be able to access and understand in order to ensure that historical values are not lost. The legislation aspect fits seamlessly with the establishment of international organizations, as these bodies help to regulate the profession.

Clause “*c- Value of international documentation,*” at the very end of the Charter, brings to light the first mention of documentation.⁴⁴

The Conference expresses the wish that:

1. Each country, or the institutions created or recognised competent for this purpose, publish an inventory of ancient monuments, with photographs and explanatory notes;
2. Each country constitute official records which shall contain all documents relating to its historic monuments;
3. Each country deposit copies of its publications on artistic and historic monuments with the International Museums Office;

⁴¹ Ibid.

⁴² Ibid.

⁴³ Ibid.

⁴⁴ Ibid.

4. The Office devote a portion of its publications to articles on the general processes and methods employed in the preservation of historic monuments;
5. The Office study the best means of utilising the information so centralised.⁴⁵

It is interesting to understand how these early principles evolved over the course of time as both technology and the understanding of heritage conservation have changed. From a Canadian federal and national context, the inventories that are used to keep a record of our historic places are the Canadian Register for Historic Places (CRHP) and the Directory of Federal Heritage Designations.⁴⁶ For Article 3, the International Museums Office no longer exists (it stopped functioning in 1946 once the United Nations was created),⁴⁷ and Canada's heritage resources are now administered by Parks Canada. In relation to Article 4, Parks Canada published *The Standards and Guidelines for the Conservation of Historic Places in Canada* in 2003 (then updated in 2010) to serve as an official document governing the practice of conservation in the country. Finally, the concept of centralized information is still an issue in conservation today. Resources such as the Federal Heritage Buildings Review Office (FHBRO) serve as archives for national sites of interest, and the *UNESCO World Heritage Centre* archives international World Heritage Sites that have "outstanding universal value."⁴⁸ The CRHP in particular serves as a federal, provincial, and territorial inventory, allowing local heritage sites (those designated by individual municipalities and cities) to be included on the list. The issue still remains of how these local heritage sites, mainly those of private ownership, collect, and distribute this information to the public, as the information contained in the CRHP is limited.

⁴⁵ Ibid.

⁴⁶ Government of Canada Parks Canada Agency, "Directory of Federal Heritage Designations," May 23, 2017, <http://www.pc.gc.ca/en/culture/dfhd.aspx>.

⁴⁷ UNESCO, "International Museums Office (IMO) - UNESCO Archives AtoM Catalogue," accessed June 11, 2017, <https://atom.archives.unesco.org/international-museums-office-imo>.

⁴⁸ UNESCO World Heritage Centre, "The Criteria for Selection."

2) International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964)

Most commonly referred to as *The Venice Charter*, the *International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964)* represents a more refined version of *The Athens Charter*, building upon over 30 years of international conservation experience. It was adopted as the first resolution at the Second Congress of Architects and Specialists of Historic Buildings in Venice in 1964.⁴⁹

As with the first critique of *The Athens Charter*, whereby the name only contained “historic monuments” this has been somewhat righted by The Venice Charter by adding the word “sites” and explicitly stating in Article 1 of the Definitions section that “the concept of a historic monument embraces not only the single architectural work but also the urban or rural setting in which is found the evidence of a particular civilization, a significant development or a historic event.”⁵⁰ While it expands the definition to include the surrounding environment of the site, it does not say that natural sites are to be protected and documented. The Venice Charter references documentation at the end of the text in Article 16:

In all works of preservation, restoration or excavation, there should always be precise documentation in the form of analytical and critical reports, illustrated with drawings and photographs. Every stage of the work of clearing, consolidation, rearrangement and integration, as well as technical and formal features identified during the course of the work, should be included. This record should be placed in the archives of a public institution and made available to research workers. It is recommended that the report should be published.⁵¹

By clearly stating that documentation is required during conservation actions, it argues that this action becomes ingrained in the conservation process. Another important point is the notion

⁴⁹ ICOMOS, “History - International Council on Monuments and Sites,” accessed May 19, 2017, <http://www.icomos.org/en/about-icomos/mission-and-vision/history?showall=&start=1>.

⁵⁰ ICOMOS, “International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964),” *ICOMOS, Paris*, 1964.

⁵¹ *Ibid.*

of how articles should be placed in public archives and made available for research to help aid future conservation actions at sites of value. The concept of dissemination of information, specifically in relation to web-based inventories, will be discussed in greater detail in Chapter 5. For sites that are privately owned and operated, contact with site owners is required to gain access to any past interventions and historical information. This act can be problematic in regards to understanding more about an historic place because of potential mismanagement of all of the years of records generated by the owner.

3) The Burra Charter (1979–2013)

First adopted in 1979, and most recently updated in 2013, the Burra Charter serves as the official ICOMOS charter for Australia.⁵² In its own words, the charter “sets a standard of practice for those who provide advice, make decisions about, or undertake works to places of cultural significance, including owners, managers and custodians”⁵³

The way in which this charter has helped to shape the practice of documentation is through its conservation process. Although the charter never references the term documentation, it still lays out processes that are essential in ensuring the conservation of sites. Article 6.1 of the charter states:

The cultural significance of a place and other issues affecting its future are best understood by a sequence of collecting and analysing information before making decisions. Understanding cultural significance comes first, then development of policy and finally management of the place in accordance with the policy.⁵⁴

This concept of collecting information is essentially the practice of documentation. Article 26 again deals with documentation more from the concept of reports, studies and policies, such

⁵² ICOMOS Australia, *The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance 2013* (Australia ICOMOS Incorporated, 2013).

⁵³ Ibid.

⁵⁴ Ibid.

that before any work is conducted on a place, these initial documents must be completed.⁵⁵ Finally, in terms of principles relating to the physical act of recording, Articles 31 and 32 cover both the concept of logging all information about an historic place and ensuring proper record keeping that can be made available to the public.⁵⁶

4) ICOMOS Principles for the Recording of Monuments, Groups of Buildings and Sites (1996)

These principles represent the first in-depth look at the act of documentation on the international stage. The text is split into five main sections that detail:

- The Reasons for Recording
- Responsibility for Recording
- Planning for Recording
- Contents of Records
- Management, Dissemination and Sharing of Records⁵⁷

The “Reasons for Recording”⁵⁸ section speaks of three main purposes as to why recording is conducted: to acquire knowledge and promote interest in heritage conservation; to create a permanent record of the site by capturing information for decision making and interpretation; and to ensure that the act of recording becomes engrained in the conservation process for all levels of heritage related projects (national, regional and local).⁵⁹

In terms of those responsible for recording, the text suggests that anyone who has an interest in ensuring the conservation of that specific site should be involved in the recording process.

⁵⁵ Ibid.

⁵⁶ Ibid.

⁵⁷ ICOMOS, “Principles for the Recording of Monuments, Groups of Buildings and Sites,” *As Adopted by ICOMOS General Assembly, Sofia, Bulgaria, October 1996*, <https://www.icomos.org/charters/archives-e.pdf>.

⁵⁸ Ibid.

⁵⁹ Ibid.

Recording planning explores the concept of ‘how’ we document.⁶⁰ Background research about a site should always be done before any work on site commences. These documents can consist of old photographs, previous condition reports, and building drawings. For the actual survey itself, the concepts of “scope, level and methods of recording” are integral to consider.⁶¹

“Content of Records” describes the types of things should be contained in a complete documentation project, including dates of construction, character-defining elements.

Finally, the “Management, Dissemination and Sharing of Records” section discusses the notion that the generated outcomes from the recording process should be made accessible to the public to be used in future conservation initiatives.⁶²

Chapter Summary

This chapter provided an analysis of the relevant ICOMOS charters that discuss the topic of cultural heritage documentation, and the theoretical framework that must be involved with any recording mission. Specific emphasis was placed by the texts reviewed on the need for the proper collection of information when doing conservation work, and the archiving and distribution of that collected information after it has been recorded.

⁶⁰ Ibid.

⁶¹ Ibid.

⁶² Ibid.

Chapter 3: Documentation References and Programs

This chapter will be discussing some major relevant documentation references and programs in North America. These documents are important to cover because they help to establish recording methodologies for the on-site work of the case studies, as well as for validating the results of both the collected data and generated products. The resources that will be discussed include:

- Recording, Documentation, and Information Management for the Conservation of Heritage Places– Guiding Principles
- The Standards and Guidelines for the Conservation of Historic Places in Canada
- Historic England–Metric Survey Specifications for Cultural Heritage vs HABS

Recording, Documentation, and Information Management for the Conservation of Heritage Places– Guiding Principles

According to Fai et al., Letellier's *Recording, Documentation, and Information Management for the Conservation of Heritage Places- Guiding Principles*, is “considered by many as the standard reference for heritage documentation.”⁶³ The main goal of the document is to “make certain that future generations know *what* was done to a heritage place, *why*, *when*, and by *whom*.”⁶⁴ It establishes the term “heritage information,” which is referred to as an integrated approach encompassing recording, documentation, and information management.⁶⁵ These three actions can be considered those that form the basic conservation approach for documenting historic places.

⁶³ Stephen Fai et al., “Building Information Modelling and Heritage Documentation,” in *Proceedings of the 23rd International Symposium, International Scientific Committee for Documentation of Cultural Heritage (CIPA)*, Prague, Czech Republic, 2011, 12.

⁶⁴ Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles*, xiii.

⁶⁵ *Ibid.*, xv.

The basis for Letellier's book is the *1996 ICOMOS Principles for the Recording of Monuments, Groups of Buildings and Sites*.⁶⁶ Therefore, the book is arranged in a manner as to analyze these principles to a greater extent than what is shown in the doctrine itself, through the use of twelve guiding principles. These principles are organized as questions, which the text examines in further detail. While all the questions are important, the ones of particular use to this research are numbers 9-12 as they encompass both how recording should be organized, and what to do with the information collected.⁶⁷ These questions are:

9. Who should have access to heritage information?
10. What level of detail is required?
11. What scope, level, and methods should apply?
12. How should records be kept and identified?⁶⁸

The text also iterates how heritage recording is a balance between three characteristics—cultural values, project goals, and site (and budget) constraints, as shown in Figure 3.1.⁶⁹ These parameters help to guide the techniques, tools, and approaches used, as each site presents its own constraints. Therefore, the practitioner must be able to adapt their workflow to them depending on the restrictions of the site.

Figure 3.1: Parameters of a recording process
From Letellier⁷⁰

⁶⁶ Ibid.

⁶⁷ Ibid.

⁶⁸ Ibid., xvii–xviii.

⁶⁹ Ibid., 37.

⁷⁰ Ibid.

Another useful piece of information discussed by Letellier is in regards to splitting the recording process into a series of levels to separate different recording actions. Letellier organizes it into reconnaissance, preliminary, and detailed.⁷¹ A reconnaissance survey provides an overview survey of a place, whereby initial photos and sketches are done in order to establish a sense of understanding of the site. Preliminary surveys build upon reconnaissance by adding measurements to the drawings such that they can be used in preparing initial documents for conservation actions. Detailed surveys are the most accurate and are employed when immediate conservation actions are required (e.g. after earthquakes) or when planning major rehabilitation works.⁷² One final note is that when going from reconnaissance to detailed surveys, the accuracy of the drawings increases. This results in more time spent doing the work, equating to higher costs.⁷³ The time factor must always be accounted for when doing recording work, because in most cases, there are limitations to the amount of time that can be spent on site.

The Standards and Guidelines for the Conservation of Historic Places in Canada

The *Standards and Guidelines* focuses mainly on the qualitative nature of documentation and the fact that it has to be involved with any conservation project.⁷⁴ What it does not do is stipulate the techniques used, the way documents are formatted, or best practices (i.e. quantitative actions), as that is not the underlying focus of the text. It speaks about themes relating to garnering a sense of understanding about a place by promoting actions such as identifying heritage values, and recognizing character-defining elements. As this research was focused around the metric recording and information sharing natures of documentation this document in particular did not

⁷¹ Ibid., 36–38.

⁷² Ibid.

⁷³ Ibid.

⁷⁴ Parks Canada, *Standards and Guidelines for the Conservation of Historic Places in Canada*.

play as integral as a role as in most conservation related studies. Therefore, practitioners in Canada not working at the federal level have to use other resources to gain an understanding of processes and validation of recording results.

Historic England–Metric Survey Specifications for Cultural Heritage vs HABS

As a subset to the documentation texts, another form of critical analysis can be shown through the examination of international documentation programs. As Canada does not currently have one of its own, the comparison will be between Historic England’s *Metric Survey Specifications for Cultural Heritage*, and The National Park Service (NPS) *Historic American Building Survey (HABS)* program. Specific attention will be paid to the physical act of recording and what each resource says about the digital recording techniques. These recording programs build off of Guiding Principles 10 and 11, which discuss the level of detail, scope and methodologies that should be applied in conservation projects.⁷⁵

Historic England’s *Metric Survey Specifications for Cultural Heritage* serves as the official specification for the Metric Survey Framework Agreement in England.⁷⁶ As it is a specifications guide, it presents best practice methodologies for all of the digital recording techniques, along with outcomes that can be generated from the captured data. It also establishes accuracy values for validating all aspects of the recording project from the initial surveys to generated end products. By being presented in a step-by-step format, it creates an easy method to organize a documentation project. The text is primarily focused on methodologies for digital recording techniques, as hand surveying is not mentioned.⁷⁷

⁷⁵ Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles*, xvii–xviii.

⁷⁶ Historic England, “Metric Survey Specifications for Cultural Heritage | Historic England,” accessed July 10, 2017, <https://historicengland.org.uk/images-books/publications/metric-survey-specifications-cultural-heritage/>.

⁷⁷ David Andrews, Jon Bedford, and Paul Bryan, *Metric Survey Specifications for Cultural Heritage* (Historic England, 2015).

The NPS *Historic American Buildings Survey (HABS)* was developed as the United States' first federal preservation program. It was established in 1933 and was created because of the need for a source to guide the documentation of architectural heritage.⁷⁸ The program establishes a series of guidelines for topics such as producing documentation, CAD and hand drawing production, and photography.⁷⁹ They revolve primarily around hand-recording techniques in order to promote interaction with the site.⁸⁰ All of these Guidelines are based around a strict set of procedures and formats because all of the information collected through the HABS program is provided to the Library of Congress for the public to access.⁸¹

Akboy's dissertation poses a critical analysis of the HABS style of documentation, and raises a variety of arguments both in favour and against this method of recording. Specifically, his work explored the evolution of the culture of HABS with technological advancement, and how this relationship will play out in the future.⁸² One important note that was discussed is that HABS is very slow to embrace digital documentation techniques because of their relationship with The Library of Congress. The Library of Congress only accepts formats that meet a 500-year durability standard, which include products such as large-format photographs, film negatives, and drawings with archival ink.⁸³ That is not to say that digital documentation techniques are not utilized when recording sites in HABS projects, as they do have a place. HABS provides a resource about using

⁷⁸ National Park Service, "Historic American Buildings Survey (HABS)," April 30, 2016, <https://www.nps.gov/hdp/habs/index.htm>.

⁷⁹ National Park Service, "HABS Guidelines," May 12, 2017, <https://www.nps.gov/hdp/standards/habsguidelines.htm>.

⁸⁰ National Park Service, "Producing HABS/HAER/HALS Measured Drawings from Laser Scans: The Pros and Cons of Using Laser Scanning for Heritage Documentation," April 30, 2016, <https://www.nps.gov/hdp/standards/laser.htm>.

⁸¹ Historic American Building Survey, "Historic American Buildings Survey- Guidelines for Historical Reports," n.d., <https://www.nps.gov/hdp/standards/HABS/HABSHistoryGuidelines.pdf>.

⁸² Serra Akboy, "The HABS Culture of Documentation with an Analysis of Drawing and Technology" (PhD diss., Texas A & M University, 2012), 3.

⁸³ *Ibid.*, iv, 97.

laser scanning in documentation projects, but their approach combines this collected data with hand-recording approaches, i.e. combination of the point cloud data with hand drawn floorplans and details.⁸⁴ As well, it does not provide standards for performing total station, photogrammetric, or laser scanning surveys, techniques that will be further discussed in Chapter 4.

After analyzing both works with respect to the end goals of this research, the *Metric Survey Specifications for Cultural Heritage* proved to be a much greater resource towards gaining a sense of validation with results and other best practices for the recording and data generating processes as compared to HABS. Although the problem of universal accessibility of information as presented in the HABS framework is certainly an issue, the scope of this thesis is not one that engages with hand recording techniques, as they are tried and true recording methodologies. The basis of this work is to understand how technology has played a role in making surveys easier to perform whilst garnering more information about these historic places to gain a stronger understanding of the site. Therefore, though useful for an academic comparison, HABS will not be discussed further in this research, while the *Metric Survey Specifications for Cultural Heritage* will be considered as an integral document to validate all of the results produced.

Chapter Summary

This chapter provided an analysis of the relevant documentation references and programs that aided in the recording methodologies for the case study sites. In particular, Letellier's *Recording, Documentation, and Information Management for the Conservation of Heritage Places– Guiding Principles*, discussed the three survey types which directly influence both time and monetary cost factors when on-site. As well, this chapter spoke about how *Metric Survey*

⁸⁴ National Park Service, “Producing HABS/HAER/HALS Measured Drawings from Laser Scans: The Pros and Cons of Using Laser Scanning for Heritage Documentation.”

Specifications for Cultural Heritage will be used to validate the accuracy values of the produced results in the case studies to determine whether they are acceptable according to the standards outlined in the text.

Chapter 4: Digital Recording Techniques

The digital heritage recording techniques that will be covered in this chapter are the total station survey, terrestrial and Unmanned Aerial Vehicle (UAV) photogrammetry, and laser scanning. To re-iterate, the following techniques were used at each of the case study sites:

- The Log Farm— Total station survey, terrestrial photogrammetry, and laser scanning;
- Prince of Wales Fort—UAV photogrammetry;
- QV66: Tomb of Nefertari and KV62: Tomb of Tutankahmen— Total station survey, terrestrial photogrammetry, and laser scanning.

The term ‘digital heritage recording’ is defined by Letellier et al. as a technique that “includes all forms of digital data capture, ranging from photographs to rectified images, CAD to photogrammetry, total stations to 3-D laser scanning, and voice to video.”⁸⁵ It is important to note that during cultural heritage documentation, traditional recording is used in conjuncture with the digital, involving skills such as hand measuring techniques and sketches.

Figure 4.1, adapted from Boehler and Heinz, showcases the various heritage recording techniques and when the technique should be used based upon the complexity and size of the object being recorded. This relates back to the notion that different recording techniques are best used during specific situations, and that not all techniques have to be used in the same project- an important theme discussed later on in this thesis in regards to the case studies. An additional category has been added to the chart in the form of UAV Photogrammetry, as seen in the 2016 CIPA Summer School Photogrammetry presentation by Georgopoulos.⁸⁶ As this was the primary

⁸⁵ Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles*, 120.

⁸⁶ Andreas Georgopoulos, “Photogrammetry” (Presentation, International Summer School on Cultural Heritage 3D Surveying and Modeling, Valencia, Spain, August 30, 2016).

recording technique used in the Prince of Wales Fort case study, it was integral that it be included on the chart.

Figure 4.1: Recording Techniques Chart

Techniques used highlighted in red. Adapted from Boehler and Heinz⁸⁷

As the use of terrestrial photogrammetry and laser scanning for cultural heritage applications are established techniques in the field of recording, an examination of only the theory and best practices will be conducted.⁸⁸ For the topic of UAV photogrammetry, a more extensive literature review has been conducted. The recent commercialization of UAVs has opened the

⁸⁷ Wolfgang Boehler and Guido Heinz, "Documentation, Surveying, Photogrammetry," in *XVII CIPA Symposium* (Recife, Brazil, 1999); Georgopoulos, "Photogrammetry."

⁸⁸ Some of the published literature examining the use of terrestrial photogrammetry and laser scanning include: Alberto Guarnieri, Nicola Milan, and Antonio Vettore, "Monitoring Of Complex Structure For Structural Control Using Terrestrial Laser Scanning (Tls) And Photogrammetry," *International Journal of Architectural Heritage* 7, no. 1 (January 1, 2013): 54–67, doi:10.1080/15583058.2011.606595; B. Bayram et al., "Comparison Of Laser Scanning And Photogrammetry And Their Use For Digital Recording Of Cultural Monument Case Study: Byzantine Land Walls-Istanbul," in *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-5-W3 (25th International CIPA Symposium 2015 (II-5/W3) - 31 August– 4 September 2015, Taipei Taiwan, Copernicus GmbH, 2015), 17–24, doi:https://doi.org/10.5194/isprsannals-II-5-W3-17-2015; Fabio Remondino, "Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning," *Remote Sensing* 3, no. 6 (May 30, 2011): 1104–38, doi:10.3390/rs3061104.

possibility of performing low-cost aerial image acquisition for the documentation of cultural heritage sites through UAV photogrammetry. The wide range of UAVs and photogrammetric software packages available sets the stage for research in this field in regards to data processing workflows for determining the best methodology for specific types of recording missions.

1) Total Station Survey

The first technique used during the digital recording of historic structures is the total station survey. A total station is an instrument that combines “three basic components — an electronic distance measuring (EDM) instrument, an electronic angle measuring component, and a computer or microprocessor.”⁸⁹ With the use of these integrated technologies, the device is able to calculate both angles and distances to survey points of interest, all with respect to its location.⁹⁰ These points of interest are also known as control points (CPs) or ground control points (GCPs). When surveying, the GCPs measured are either target based or natural. Target control points consist of checkerboard targets or special photogrammetric software targets (i.e. PhotoScan) placed on/around the object of interest. Natural control points are distinguishable points on the object of interest such as sharp corners or circular details.

The ways in which the distances are actually calculated are through the use of the electronic distance measuring (EDM) unit. There are two main ways that it does this: by measuring a reflector or reflectorless object. These categories are also known as Prism and Non-Prism modes respectively. When the term reflector is spoken of, it represents the use of an external object (prisms) to reflect the signal back to the instrument.⁹¹ By measuring the phase shift of an infrared

⁸⁹ Charles D. Ghilani and Paul R. Wolf, *Elementary Surveying: An Introduction to Geomatics*, Fourteenth edition (Boston: Pearson, 2015), 183.

⁹⁰ Gopi, Sathikumar, and Madhu, *Advanced Surveying*, chap. 7.

⁹¹ *Ibid.*, chap. 8.

light emitted by the EDM and then returned back by the prism, the distance and angle are calculated.⁹²

For Non-Prism modes, points can be surveyed without the use of a prism. This is beneficial because a secondary station setup, either by positioning a prism on a tripod, or by an additional team member holding a prism on a rod, does not need to occur. Therefore, control points (of target or natural nature) can be taken rather quickly as compared to purely surveying using prisms.

While surveying, both Prism and Non-prism modes are used in conjunction with one another due to the relative ease of switching between the two settings on the total station. Additionally, there will be situations where one method works better than others.

Surveying Sources of Error

According to the text *Elementary Surveying: An Introduction to Geomatics*, there are a number of sources of error to take into account when using the total station.⁹³ These can be grouped by either natural or personal errors.⁹⁴ Natural errors account for variables such as wind, temperature (unequal expansion of instrument parts), refraction (bending of light beam), and tripod settlement.⁹⁵ These variables are not as serious contributors to the overall measurement error as personal errors are. Personal errors are those that the operator of the total station has full control of, and should always be accounted for. These include the instrument not being set exactly over the survey point of interest, not centering the levelling bubble perfectly, and poor focusing due to the user's eye becoming tired.⁹⁶ In particular, the error about not centering the bubble level can be deemed as most critical. Because of the high accuracy of the total station, it is integral that the

⁹² Ibid.

⁹³ Ghilani and Wolf, *Elementary Surveying*.

⁹⁴ Ibid., 218–19.

⁹⁵ Ibid.

⁹⁶ Ibid.

instrument be properly leveled at each station setup. This is because of compounded errors when moving the instrument from one surveying position to the next.

Establishing the Survey

There are two different ways in which a coordinate system were established for this research work: ‘Orientation with Angle’ or ‘Orientation with Coordinates’ setting in the Leica TS06 total station. The ‘Orientation with Angle,’ setting establishes a new survey by orienting the total station to a specific angle, usually true north. With ‘Orientation with Coordinates,’ the survey links to an existing system. Resection techniques were used on-site when the total station had to be moved to survey more points. The premise behind the resection is that as long as at least two previously surveyed points are visible from the new station setup, the total station is able to calculate its new position due to the trigonometric relationships between them. For good practice, at least three to four points should be used in the resection to ensure a more accurate result.

2) Photogrammetry

Photogrammetry is defined as the science of extracting measurements from photographs. Photogrammetry is conducted before, after, or concurrent with the total station survey. Because it uses photographs as baseline information for generating models, it is known as an image-based recording technique.

In regards to cultural heritage recording applications, the primary benefit of using the technique is that it “allows the reconstruction of an object and the analysis of its characteristics without physical contact with it.”⁹⁷ This is quite an important factor, as its non-intrusive nature ensures that it will not harm the physical fabric of sites that are documented.

⁹⁷ Karl Kraus and Ian Harley, *Photogrammetry: Geometry from Images and Laser Scans*, 2. ed, De Gruyter Textbook (Berlin: de Gruyter, 2007), 2.

Importance of Photography

As photography is the key element in photogrammetry, it is important to have a strong understanding of photography in order to generate the best results possible. Attributes such as focal length, aperture, shutter speed, and ISO are very important when taking photographs to ensure a good quality image. DSLR cameras are the preferred device of choice to capture photographs because of attributes like the ability to change the lens, and the larger sensor sizes than a traditional cellphone camera.⁹⁸ The sensor size of a camera is also a very important variable to consider. The larger the sensor, the more detailed images that can be produced (i.e. more pixels per image). Camera planning sheets are used in order to keep a record of the camera specifications, which is good practice for posterity record keeping.

Another component of photography is camera calibration. Camera calibration is the act of determining the internal geometry of the camera in order to determine parameters to increase the overall accuracy of the final model.⁹⁹ Traditionally, these have been calculated using complex mathematical formulae, but today are automatically calculated by photogrammetric software.¹⁰⁰

Basic Photogrammetric Theory

Photogrammetry is based around the concept of central projection. From dictionary.com, central projection is defined as “a projection of one plane onto a second plane such that a point on the first plane and its image on the second plane lie on a straight line through a fixed point not on either plane.”¹⁰¹ In the case of photogrammetry, the first plane is the photograph, and the second

⁹⁸ Stylianidis, Georgopoulos, and Remondino, “Chapter 5- Basics of Image-Based Modelling Techniques in Cultural Heritage 3D Recording,” 266–67.

⁹⁹ Ibid., 270–72.

¹⁰⁰ Ibid.

¹⁰¹ Dictionary.com, “Central Projection,” accessed July 9, 2017, <http://www.dictionary.com/browse/central-projection>.

plane is the object of interest. This is illustrated in Figure 4.2 from Luhmann et al. In this case, the fixed point not on either plane is represented by O' . The point on the first plane is illustrated by P' , while corresponding to point P on the second plane. Each one of the lines coming out of O' is called a ray. A group of these rays is called a bundle. By doing this application for the same point in at least two images, we are able to find these object points in 3D space.¹⁰² Two or more images are required because of the fact that a single photograph only has the ability to show two dimensions of a three-dimensional object.¹⁰³

Figure 4.2: Principle of Central Projection
From Luhmann¹⁰⁴

These basic principles are all employed in photogrammetric software used today, except at a much more complicated level. The process is now automated and done with the use of the ‘Structure from Motion’ algorithm.¹⁰⁵ Structure from Motion (SfM) is different from traditional

¹⁰² T Luhmann et al., *Close range photogrammetry: principles, techniques and applications*, 2011, 2.

¹⁰³ Ibid.

¹⁰⁴ Ibid., 6.

¹⁰⁵ Efstratios Stylianidis and Andreas Georgopoulos, “Digital Surveying in Cultural Heritage: The Image-Based Recording and Documentation Approaches,” in *Handbook of Research on Emerging Technologies for Digital Preservation and Information Modeling* (IGI Global, 2017), 129.

photogrammetry because of how it analyzes the images. By using a large number of photographs, and finding the same point in more than two images, the software is automatically able to perform a bundle adjustment of the camera rays in each image.¹⁰⁶ The bundle adjustment also calculates the camera location (with respect to the other images) and internal camera geometry (camera calibration).¹⁰⁷ This fulfills all of the requirements for the reconstruction of a series of two-dimensional images into an individual points in a three-dimensional coordinate system, also called establishing a sparse point cloud.

The next step in the process is the creation of a denser point cloud, which creates more points at pixel or sub-pixel level depending on the quality of the image. After this step has been calculated, a mesh can be created based off of the dense cloud points. Meshes can be used for geometrical modelling applications. After the mesh has been established, orthophotos (rectified photographs of the object of interest) can be generated from it. These are particularly useful for measured drawing or condition assessment purposes.

There is a variety of photogrammetric software available, including Agisoft PhotoScan, Bentley ContextCapture, Pix4d, Photomodeler, and Micmac. PhotoScan is one of the more common software used, and is a commercial software. It is considered to be a “black box” type, whereby the user does not know the internal algorithms. Micmac, on the other hand, is an open source software that allows a great deal of customization for its users.¹⁰⁸ For the purposes of this research, PhotoScan and ContextCapture were both used in the data processing stages for the case studies, as they were available to use in the Carleton Immersive Media Studio research lab.

¹⁰⁶ Stylianidis, Georgopoulos, and Remondino, “Chapter 5- Basics of Image-Based Modelling Techniques in Cultural Heritage 3D Recording,” 273.

¹⁰⁷ Ibid.

¹⁰⁸ NIDI-KNAW, “MicMac Software,” accessed July 9, 2017, <http://www.nidi.nl/en/research/al/micmac/software>.

CIPA 3x3 Rules

When speaking about photogrammetric best practices, no review is complete without a discussion of the CIPA 3x3 Rules.¹⁰⁹ These are the principles that guide the concept of architectural photogrammetry, and should be at the forefront of any photogrammetric project. One important point of emphasis is the stereo photocover. As stated in Luhmann et al., “Object areas which are not visible in the image cannot be reconstructed from it.”¹¹⁰ This is why the stereo photocover principle is so important as to ensure that image details are not missed and the fact that enough overlap is captured to aid in the image alignment process.

Table 4.1: 3x3 Rules of Photogrammetry
Adapted from Waldhäusl and Ogleby¹¹¹

3 Geometrical rules	3 Photographic rules	3 Organizational rules
Control Information (Acquire GCPs)	Camera Properties- fix focus distance	Record Photo Layout through sketches
Stereo Photocover (Take a ring of images around the subject with at least 60% overlap)	Camera Calibration- medium format camera is preferred	Log the Metadata
Detail Stereo Photocover	Image Exposure should be consistent	Archive the information

Ground Sample Distance (GSD)

Ground sample distance (GSD) is determined in order to understand the size of one pixel on the image, and how that corresponds to a set measurement on the object that is being surveying. GSD is expressed in millimetres, or centimetres. For example, if the required GSD is 5mm, this means that 1 pixel on the camera image corresponds to 5mm on the object. It is also representative

¹⁰⁹ Peter Waldhäusl and C. L. Ogleby, “3 X 3 Rules for Simple Photogrammetric Documentation of Architecture,” *International Archives of Photogrammetry and Remote Sensing* 30 (1994): 3.

¹¹⁰ Luhmann et al., *Close range photogrammetry*, 2.

¹¹¹ Waldhäusl and Ogleby, “3 X 3 Rules for Simple Photogrammetric Documentation of Architecture,” 3.

of the distance between pixel centers, whereby a GSD of 5mm means that there is a 5mm distance from one pixel center to the next.¹¹² The formulas used for calculating GSD are shown below:

Figure 4.3: Visualization of GSD concept
Created by author

$$\text{GSD} = \frac{\text{Pixel Size (px)}}{\text{focal length (d)}} \times \text{Distance to object (D)} \quad (\text{Equation 4.1})$$

Equations (4.2) and (4.3) explain how to calculate the overlap between two camera positions which helps to ensure a sufficient photocover:

$$\text{baseline distance between photographs (b)} = \left(1 - \frac{\text{Overlap \%}}{100}\right) \times W \quad (\text{Equation 4.2})$$

$$W = \frac{\text{Distance to object (D)}}{\text{focal length (d)}} \times w(\text{sensor width}) \quad (\text{Equation 4.3})$$

¹¹² Stylianidis, Georgopoulos, and Remondino, “Chapter 5- Basics of Image-Based Modelling Techniques in Cultural Heritage 3D Recording,” 263.

Figure 4.4: Photograph overlap diagram
Created by author

Figure 4.5: Relationship to help determine distance between photographs
Created by author

Best Practice Guidelines

When performing a photogrammetric survey, along with following the 3x3 Rules, the following factors should be carefully planned for to avoid errors while taking photographs and processing the data:

- Ensuring that the GSD is “at least 2–3 times smaller than the smallest geometric detail to be captured and digitized”¹¹³
- Images should be taken as to ensure that all the details are visible in at least 2-3 images; ¹¹⁴
- Scale bars should be placed in some images if GCP acquisition is not available; ¹¹⁵
- Keep the camera parameters consistent (i.e. use manual focus instead of automatic zoom). ¹¹⁶
- If using a zoom lens, tape the lens on the specific focal length to ensure it does not change;
- Along with target control points, also capture corners of details for added measurement validation.

PhotoScan Processing Workflow

As PhotoScan software was used in all four case studies, instead of detailing the procedure in each one, it is presented here. Each of the case studies will elaborate more on the difficulties encountered when using the software, and how these challenges were overcome. A brief commentary about some of the steps will be discussed below, specifically in regards to best practice methodologies learned during experimentation with the software.

¹¹³ Ibid., 268.

¹¹⁴ Ibid.

¹¹⁵ Ibid.

¹¹⁶ Ibid.

Figure 4.6: PhotoScan Processing Workflow

Quality Check

When using photogrammetric software, it is important to check the quality of the image before using it in the model. PhotoScan has a built in function that outputs an estimated image quality of the photographs. This image quality is based off of the sharpness of the photograph. Those images of poor quality i.e. blurry or unfocused, can impact the overall registration procedure.¹¹⁷ Therefore, the PhotoScan manual suggests removing any photos with a quality of

¹¹⁷ Agisoft LLC, “Agisoft PhotoScan User Manual Professional Edition, Version 1.1,” 2014, http://www.agisoft.com/pdf/photoscan-pro_1_1_en.pdf.

0.5 or less.¹¹⁸ From experience using the software, it is best to remove any outlier values even if their value is greater than 0.5. For example, if most of the images are in the 0.8 to 0.9 range, removing images that have a 0.7 quality is sufficient unless they provide views that are crucial to the reconstruction of the model.

Masking Photographs

Masking is a process whereby areas that are not of interest are selected and removed from the image alignment process. As some photographs contain details that are not useful in the creation of the final dense cloud model of the object of interest (i.e. the sky or trees) these areas can be manually deselected using masking so they do not appear in the generated models. The importance of masking is that it cuts down the post-processing time required to clean the model of any residual points that are not a part of the final output.

Importing and Identifying Control Points

There are two main ways to identify control points in PhotoScan. The first is the automatic method, whereby PhotoScan is able to distinguish specially coded targets and apply the control point markers to those targets. The other way is through manual acquisition, whereby the user views each of the images and marks the location of the control points on the image. This method is much longer, but for sites that have pre-established control points, is the method of choice. For the scaling of a photogrammetric model, at least three control points are required, and they should not be collinear or coplanar. If more can be taken, then the approach of “the more the better” is used, as more control points help to validate the accuracy of the model.¹¹⁹

¹¹⁸ Ibid.

¹¹⁹ Stylianidis, Georgopoulos, and Remondino, “Chapter 5- Basics of Image-Based Modelling Techniques in Cultural Heritage 3D Recording,” 268. 268.

Aligning Photographs

In most cases, using the default settings in the alignment window in PhotoScan is sufficient. Because the purpose of this research was to experiment with various software settings and parameters in order to generate the best quality models, adjusting these parameters was of interest.

The two main parameters in the alignment process are ‘Key Points’ and ‘Tie Points.’ From the PhotoScan User Manual, ‘Key Points’ are the number of “feature points on every image to be taken into account during current processing stage. Using zero value allows PhotoScan to find as many key points as possible, but it may result in a big number of less reliable points.”¹²⁰

‘Tie Points’ “indicates [the] upper limit of matching points for every image.”¹²¹ Tie points means that it chooses a number of points (whatever the user sets the value to) from the found key points to use to register the images together. By default, PhotoScan sets these settings at 40,000 and 4,000 respectively. In the data processing for The Log Farm and Prince of Wales Fort, 0 ‘Key Points’ and 5000 ‘Tie Points’ were used as these values came from data processing workflows during the 2016 CIPA Summer School. The final step in this stage is to deselect ‘constrain features by mask,’ as that function should only be enabled if the object was moving during the survey.¹²² In the case studies examined, the objects were stationary.

Point Density Calculation

Section 2.1.2 of *Metric Survey Specifications for Cultural Heritage* describes the accuracy of generated point clouds through the use of the term point density.¹²³ Point density is defined as the average distance between respective points. Therefore, if a point cloud had a density of 1 metre,

¹²⁰ Agisoft LLC, “Agisoft PhotoScan User Manual Professional Edition, Version 1.1.”

¹²¹ Ibid.

¹²² Ibid.

¹²³ Andrews, Bedford, and Bryan, *Metric Survey Specifications for Cultural Heritage*.

there would be four points in a 1 metre squared area. Using this basic principle, it is possible roughly calculate the point density based off of a plane of known area. It is important to note that the main assumption this method uses is the fact that the points are in a regular grid pattern spaced at even intervals.

The first step is to calculate the number of known points in a metre-squared area based off of the required point density. The relationship between the point density and number of points in a row is such that there is one more point in each row than there is a space. This is shown by the formula and figure below:

$$\# \text{ of points in 1 row} = (\text{number of spaces} + 1) \text{ (Equation 4.4)}$$

Figure 4.7: Diagram representing meaning of points and spaces concept
Created by author

Because of the assumption that the points are in a perfect square, to find the total number of points, we take the square of that value.

$$\# \text{ of points in square area} = (\text{number of spaces} + 1)^2 \text{ (Equation 4.5)}$$

The distance of the space (distance between two points) as seen in Figure 4.7 is known as the point density. These formulas give a baseline number of points to which the point density corresponds to in a 1 meter squared area. Working backwards, it is possible to calculate the point density based off of a planar area that may or may not be larger than 1 meter squared. The first step is determining the number of points in a segment of the point cloud by applying a 2D Polygon to it using the free open source software CloudCompare.

$$\# \text{ of points in } 1m^2 = \frac{\# \text{ of points in selected segment}}{\text{Area of segment plane (m}^2\text{)}} \text{ (Equation 4.6)}$$

$$\text{Point Density (mm)} = \frac{1m}{(\text{Number of Spaces})} \text{ (Equation 4.7)}$$

Because of the defined relationship between the number of points in a square area and number of spaces, replacing the ‘number of spaces’ parameter with $(\sqrt{\# \text{ of points in } 1m^2} - 1)$, gives the final formula for determining point density:

$$\text{Point Density (m)} = \frac{1m}{(\sqrt{\# \text{ of points in } 1m^2} - 1)} \text{ (Equation 4.8)}$$

To illustrate this concept, a basic example has been shown below:

Figure 4.8: Sample Point Density Illustration
Created by author

$$\text{Point Density (mm)} = \frac{1m}{(\sqrt{16} - 1)}$$

$$\text{Point Density (mm)} = \frac{1m}{(3)} = 0.33m$$

3) UAV Photogrammetry

Complementary to terrestrial photogrammetry is UAV photogrammetry. The goal of this section is to provide a broad overview of the technique, the hardware used, and data processing methodologies, as they vary slightly from that of terrestrial photogrammetry. As UAVs can be equipped with cameras, they are also able to capture aerial photographs and video. This prospect makes them a very appealing choice as a digital documentation tool for aerial photogrammetry.

According to the Canadian Aviation Regulations, the term ‘Unmanned Aerial Vehicle’ is defined as “a power-driven aircraft, other than a model aircraft, that is designed to fly without a human operator on board.”¹²⁴ UAVs themselves are known by many different names, including remotely piloted vehicles (RPV), drones, and remotely piloted aircraft system (RPAS).¹²⁵ The *International Civil Aviation Organization* (ICAO), of which Canada is a member, uses the term RPAS as their international standard.¹²⁶ For the context of this research, the term UAV will be used throughout.

In addition to the UAV definition, there is also a term called ‘unmanned aerial system’ (UAS). This is used to describe the UAV itself, as well as the ground control station (GCS).¹²⁷ The GCS is the operator on the ground who is controlling the UAV. This can consist of a formal control room, or an individual operating the system with a handheld remote controller on site.

¹²⁴ Government of Canada-Legislative Services Branch, “Consolidated Federal Laws of Canada, Canadian Aviation Regulations,” February 9, 2017, <http://laws-lois.justice.gc.ca/eng/regulations/SOR-96-433/FullText.html#h-779>.

¹²⁵ M. Bolognesi et al., “Testing the Low-Cost RPAS Potential in 3D Cultural Heritage Reconstruction,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5-W4 (WG V/4, CIPA 3D-Arch 2015- 3D Virtual Reconstruction and Visualization of Complex Architectures (XL-5/W4) - 25-27 February 2015, Avila, Spain: Copernicus GmbH, 2015), 229–35, doi:10.5194/isprsarchives-XL-5-W4-229-2015; Francesco Nex and Fabio Remondino, “UAV for 3D Mapping Applications: A Review,” *Applied Geomatics* 6, no. 1 (March 1, 2014): 1–15, doi:10.1007/s12518-013-0120-x.

¹²⁶ ICAO, “ICAO Circular 328, Unmanned Aircraft Systems (UAS). Technical Report. International Civil Aviation Authority” (Montreal, Canada, 2011).

¹²⁷ Nex and Remondino, “UAV for 3D Mapping Applications,” 1.

The practice of using UAVs for photogrammetric applications can be traced back to the 1979 and 1980 tests by Przybilla and Wester-Ebbinghaus on the *Schwebebahn (monorail) Wuppertal*.¹²⁸ The advent of the specific term ‘UAV photogrammetry’ can be attributed to the work of Henri Eisenbeiss, whose dissertation in 2009 provided new insight into the use of UAVs for aerial photogrammetric applications.¹²⁹ Eisenbeiss describes UAV photogrammetry as “a photogrammetric measurement platform, which operates remotely controlled, semi-autonomously, or autonomously, without a pilot sitting in the vehicle.”¹³⁰ Additionally, the article titled “UAV for 3D mapping applications: a review,” authored by Nex and Remondino, served as an important source of information to understand the state of the arts in this field.

The main goal of this subsection of the thesis is to understand how UAV photogrammetry is being used as a low-cost alternative tool for the documentation of cultural heritage sites. This review takes on a Canadian context in regards to the legislation governing UAVs, but the overall workflow component can be applied to countries worldwide.

UAV History

In today’s society, UAVs are available for commercial purchase from online retailers and electronics stores. Simply put, they are accessible for common civilians to own. This occurrence was not always the case, as UAVs were initially designed for (and still used for) military purposes. Military applications involved unmanned inspection, surveillance, and terrain mapping.¹³¹ These same applications are the reason as to why UAVs are popular with cultural heritage practitioners,

¹²⁸ Henri Eisenbeiß, *UAV Photogrammetry* (ETH Zurich, Switzerland:, 2009), 13; “Photogrammetry Round the World,” *The Photogrammetric Record* 10, no. 55 (1980): 107–12, doi:10.1111/j.1477-9730.1980.tb00012.x; I. Colomina and P. Molina, “Unmanned Aerial Systems for Photogrammetry and Remote Sensing: A Review,” *ISPRS Journal of Photogrammetry and Remote Sensing* 92 (June 2014): 79–97, doi:10.1016/j.isprsjprs.2014.02.013.

¹²⁹ Eisenbeiß, *UAV Photogrammetry*.

¹³⁰ Ibid., 2.

¹³¹ Nex and Remondino, “UAV for 3D Mapping Applications,” 1.

as they enable the ability to rapidly survey areas and acquire a large amount of data in a short time frame.¹³²

UAV Typologies

There are many different ways of classifying UAVs because they vary depending on a wide range of factors. Nex and Remondino cite UVS International's three main UAV categories. UVS International is an organization that promotes the non-military use of UAVs, as well as studying rules, regulations, and standards.¹³³ These criteria are:

- Tactical UAVs (short to medium range, altitude of few hundred metres)¹³⁴
- Strategical UAVs (long endurance, altitude higher than 20,000m)¹³⁵
- Special Task UAVs (combat/decoys systems)¹³⁶

Eisenbeiss provides an alternate way in which UAVs can be classified, which is by being considered as unpowered or powered, as well as lighter than air or heavier than air.¹³⁷ Table 4.2 displays the various UAV types.

From the literature reviewed, along with the author's own independent research into UAVs for this thesis, the most common platform used for UAV photogrammetry based on the factors of low cost and usability, is of the rotary wing type. Specifically, quadrotors and multi-rotors (hexacopters, octocopters) were used in articles consulted.¹³⁸

¹³² M. Lo Brutto, A. Garraffa, and P. Meli, "UAV Platforms for Cultural Heritage Survey: First Results," in *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-5 (ISPRS Technical Commission V Symposium (Volume II-5) - 23-25 June 2014, Riva del Garda, Italy, Copernicus GmbH, 2014), 227–34, doi:10.5194/isprsannals-II-5-227-2014.

¹³³ UVS International, "Who We Are and What We Do – UVS International," accessed December 18, 2016, <http://uvs-international.org/about/who-we-are-and-what-we-do/>.

¹³⁴ Nex and Remondino, "UAV for 3D Mapping Applications," 2.

¹³⁵ Ibid.

¹³⁶ Ibid., 3.

¹³⁷ Eisenbeiß, *UAV Photogrammetry*, 34.

¹³⁸ These articles include: Bolognesi et al., "Testing the Low-Cost RPAS Potential in 3D Cultural Heritage Reconstruction"; M. Faltýnová et al., "Building Facade Documentation Using Laser Scanning and Photogrammetry and Data Implementation into BIM," in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLI-B3 (XXIII ISPRS Congress, Commission III (Volume XLI-B3) - 12-19 July 2016, Prague, Czech Republic, Copernicus GmbH,

Table 4.2: Classification of UAVs
Adapted from Eisenbeiss¹³⁹

	Lighter than air	Heavier than air		
		Flexible Wing	Fixed Wing	Rotary Wing
Unpowered	Balloon	Hang glider	Gliders	
		Paraglider		
		Kites		
Powered	Airship	Paraglider	Propeller	Single Rotors
			Jet Engines	Coaxial
				Quadrotors
				Multirotors

Canadian UAV Regulations

The final acquisition of data is the ultimate goal of using UAVs for photogrammetric purposes. This task should never compromise the safety of the team or public. Therefore, it can be argued that the most important step in the UAV photogrammetric workflow is the due diligence put in by the cultural heritage practitioners in regards to safety procedures when using UAVs. This is in regards to abiding by the legal requirements and legislation for flying UAVs in the countries they are operating in. By understanding the safety procedures and protocols, it helps to minimize the possibility that the UAV will cause damage to both humans on the ground (i.e. the drone takes

2016), 215–20, doi:10.5194/isprs-archives-XLI-B3-215-2016; I. Aicardi et al., “UAV Photogrammetry with Oblique Images: First Analysis on Data Acquisition and Processing,” *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLI-B1 (June 6, 2016): 835–42, doi:10.5194/isprs-archives-XLI-B1-835-2016; Tesse D. Stek, “Drones over Mediterranean Landscapes. The Potential of Small UAV’s (Drones) for Site Detection and Heritage Management in Archaeological Survey Projects: A Case Study from Le Pianelle in the Tappino Valley, Molise (Italy),” *Journal of Cultural Heritage* 22 (November 2016): 1066–71, doi:10.1016/j.culher.2016.06.006; K. A. Hashim et al., “Integration of Low Altitude Aerial & Terrestrial Photogrammetry Data in 3D Heritage Building Modeling,” in *2012 IEEE Control and System Graduate Research Colloquium*, 2012, 225–30, doi:10.1109/ICSGRC.2012.6287166; M. Bolognesi et al., “Accuracy of Cultural Heritage 3D Models by RPAS and Terrestrial Photogrammetry,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5 (ISPRS Technical Commission V Symposium (Volume XL-5) - 23–25 June 2014, Riva del Garda, Italy, Copernicus GmbH, 2014), 113–19, doi:10.5194/isprsarchives-XL-5-113-2014; Fausta Fiorillo et al., “3d Surveying and Modelling of the Archaeological Area of Paestum, Italy,” *Virtual Archaeology Review* 4, no. 8 (May 20, 2013): 55–60, doi:10.4995/var.2013.4306; Z. Sun and Y. K. Cao, “Data Processing Workflows from Low-Cost Digital Survey to Various Applications: Three Case Studies of Chinese Historic Architecture,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5-W7 (25th International CIPA Symposium 2015 (XL-5/W7) - 31 August-4 September 2015, Taipei, Taiwan, Copernicus GmbH, 2015), 409–16, doi:10.5194/isprsarchives-XL-5-W7-409-2015.

¹³⁹ Eisenbeiß, *UAV Photogrammetry*, 34.

off on the operator and injures someone) and other aircraft in the sky. For the purposes of this literature review, Canadian UAV legislation will be reviewed.

Transport Canada has a series of protocols to follow when flying UAVs in Canadian airspace, with the most important regulation being the Special Flight Operations Certificate (SFOC). These regulations are governed by the enabling legislation, *The Canadian Aeronautics Act*.¹⁴⁰ The SFOC is the document allowing the use of UAVs for any application other than flying for fun and pleasure.¹⁴¹ It helps to ensure that operators will use their UAVs safely. It contains information such as how, when, and where the UAV will be used, maximum flight altitude, the operating area, and safety risk plans.¹⁴²

The SFOC application must be submitted to the specific Transport Canada office in the region that flights are planned. For the processing of SFOC applications, it is based on a first-come-first-served basis. The Transport Canada website says that they aim to process the applications within a minimum of 20 working days.¹⁴³

This process of 20 working days can be a hindrance to projects with tight timelines and/or budget constraints. Sometimes due to the severity of the project (i.e. UAV used for surveillance of collapsed buildings and/or photogrammetric models of existing conditions), this timeline is not feasible for the practitioner.

There are some stipulations in the Transport Canada documents that allow for specific exemptions to the SFOC process. If the UAV has a take-off weight not exceeding one kilogram,

¹⁴⁰ Transport Canada Government of Canada, "Aeronautics Act (R.S., 1985, C. A-2)," October 15, 2009, <http://www.tc.gc.ca/eng/acts-regulations/acts-1985ca-2.htm>.

¹⁴¹ Government of Canada; Transport Canada; Safety and Security Group, "Flying Your Drone Safely and Legally."

¹⁴² Civil Aviation Government of Canada; Transport Canada; Safety and Security Group, "Getting Permission to Fly Your Drone," June 7, 2016, <https://www.tc.gc.ca/eng/civilaviation/opssvs/getting-permission-fly-drone.html>.

¹⁴³ Ibid.

then the user is eligible to operate under a regulatory exemption.¹⁴⁴ Another exemption category is when the UAV is between one and 25kg. Under this criteria, the UAV pilot must have successfully completed a pilot ground school program.¹⁴⁵ These exemptions only take effect if the UAV is operated away more than nine kilometers from built up areas and airports.¹⁴⁶ This essentially means that the exemptions are only good for isolated sites, which is not always the case for structures with heritage value. One last note of importance: if cultural heritage specialists do not abide by the laws set out by Transport Canada regarding the use of UAVs, the consequences can be fines up to \$25,000 and/or jail time.¹⁴⁷

UAV Photogrammetry and Cultural Heritage Documentation

Since the 2009 dissertation by Eisenbeiss, the popularity of using the platform for documentation has only increased due to technological advances. In the archaeological field in particular, UAVs offer the ability to document excavations at different points in time and then be compared to one another.¹⁴⁸

Based on literature reviewed, UAVs have been primarily used for one of two main applications. These involve complimenting an initial survey by capturing inaccessible roof areas or facades over 4 floors,¹⁴⁹ or to complete the survey in its entirety.¹⁵⁰ Shown in Table 4.3 is a

¹⁴⁴ Transport Canada Government of Canada, "Exemption from Paragraph 571.08(1)(b) of the Canadian Aviation Regulations," December 21, 2016, <http://www.tc.gc.ca/civilaviation/regserv/affairs/exemptions/docs/en/2880.htm>.

¹⁴⁵ Transport Canada Government of Canada, "Exemption from Paragraph 571.08(1)(b) of the Canadian Aviation Regulations," December 21, 2016, <http://www.tc.gc.ca/civilaviation/regserv/affairs/exemptions/docs/en/2879.htm>.

¹⁴⁶ Civil Aviation Government of Canada; Transport Canada; Safety and Security Group, "Staff Instruction (SI) No. 623-001," December 22, 2014, http://www.tc.gc.ca/eng/civilaviation/standards/general-recavi-uav-4161.html#toc8_0.

¹⁴⁷ Government of Canada; Transport Canada; Safety and Security Group, "Flying Your Drone Safely and Legally."

¹⁴⁸ Nex and Remondino, "UAV for 3D Mapping Applications," 7.

¹⁴⁹ Faltýnová et al., "Building Facade Documentation Using Laser Scanning and Photogrammetry and Data Implementation into BIM," 217.

¹⁵⁰ Aicardi et al., "UAV Photogrammetry with Oblique Images"; Bolognesi et al., "Testing the Low-Cost RPAS Potential in 3D Cultural Heritage Reconstruction"; Z. Xu et al., "Three Dimensional Reconstruction of Large Cultural Heritage Objects Based on UAV Video and TLS Data," in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLI-B5 (XXIII ISPRS Congress,

comparison of UAV photogrammetry to its traditional aerial and terrestrial equivalents in terms of key photogrammetric parameters.

Table 4.3: Comparison of Aerial, Terrestrial and UAV Photogrammetry

Adapted from Eisenbeiss¹⁵¹

	Aerial	Terrestrial	UAV
Planning	Semi-Automatic	Manual	Manual or Automatic
Data Acquisition when flying	Assisted/manual	Automated/assisted/manual	Automated/assisted/manual
Size of area	km ²	mm ² -m ²	m ² -km ²
GSD	cm-m	mm-dm	mm-m
Distance to Object	100m-10km	cm-300m	m-km
Camera Orientation	Normal to object	Normal/Oblique	Normal/Oblique
Examples of Typical Uses	Large scale mapping applications	Documentation of buildings/artifacts	Small and large scale mapping, documentation of buildings/sites

The workflow in Figure 4.10 can be used as a basis for UAV image processing. It is important to note that a separate category can be attached to mission planning that contains all of the safety formalities and applications discussed earlier (i.e. SFOC). Additional information such as completing a flight log after each flight can also go in this category. The basic flight logbook contains providence information about the flight (i.e. flight pattern, time of flight, battery life, wind speeds, temperature, etc.). Websites such as Airdata UAV are able to track the metadata contained in UAV memory cards.¹⁵²

Commission V (Volume XLI-B5) - 12-19 July 2016, Prague, Czech Republic, Copernicus GmbH, 2016), 985–88, doi:10.5194/isprs-archives-XLI-B5-985-2016.

¹⁵¹ Eisenbeiß, *UAV Photogrammetry*, 3.

¹⁵² Airdata.com, “Airdata UAV - Flight Data Analysis for Drones,” 2017, <https://airdata.com/>.

Figure 4.9: UAV Data Acquisition Workflow
From Nex and Remondino¹⁵³

Comparison of UAVs

There are many UAVs available for commercial purchase. Some have exhibited more success for UAV photogrammetric applications than others. Almost all of the articles explored used a rotary wing system, which is the type of UAV that will be presented here for a brief comparison. A common theme throughout the articles was the goal of low cost data acquisition. After reviewing the cost of the UAVs used in some of the test flights the average was around \$2000 USD, which can be used as a benchmark figure to compare future UAV tests.¹⁵⁴ Some common UAVs at that price point or lower include the DJI Phantom 4 (Figure 4.11) and 4 Pro, 3DR Solo, and Yuneec Typhoon.¹⁵⁵

Another way to classify potential UAVs for photogrammetric uses is if they come with a built in camera feature. Those that do come with one are limited in regards to their focal length and sensor size, and therefore the UAV must be flown closer to the object of interest in order to

¹⁵³ Nex and Remondino, "UAV for 3D Mapping Applications," 5.

¹⁵⁴ The articles reviewed were: Bolognesi et al., "Accuracy of Cultural Heritage 3D Models by RPAS and Terrestrial Photogrammetry"; Bolognesi et al., "Testing the Low-Cost RPAS Potential in 3D Cultural Heritage Reconstruction"; Sun and Cao, "Data Processing Workflows from Low-Cost Digital Survey to Various Applications."

¹⁵⁵ myfirstdrone.com, "May 2017 Top 20 Best Drones For Sale List | MyFirstDrone," *My First Drone*, May 1, 2017, <https://myfirstdrone.com/tutorials/buying-guides/best-drones-for-sale/>.

ensure the same photograph resolution as a camera with a larger sensor. The positive attribute is that they are a complete system and do not require the purchase of extra features (camera and gimbal). Additionally, the camera can be oriented at a variety of angles for oblique images.

UAVs that do not have a built in camera require additional steps before they become operational for photogrammetry (i.e. the addition and attachment of a camera and gimbal system). The positive attributes of this type of system are that they are able to capture higher quality images during each flight test because of the addition of DSLR cameras.

Figure 4.10: Rotary Wing UAV Example- DJI Phantom 4
From¹⁵⁶

Data Acquisition

There are a variety of parameters that must be considered when acquiring images with UAV flights. The first is GSD. Calculating GSD for UAV flights varies slightly as compared to calculating it for capturing vertical facades. It is important to set the *Distance to the object* variable, shown as D in Figures 4.3 and 4.5, as the farthest point away from the camera that is to be surveyed, instead of the object closest to the camera. By doing so, it ensures that the point farthest away from the sensor will still have sufficient resolution for digital reconstruction purposes. If the GSD is set at the closest object, then details of the farther object will not be displayed with the same resolution.

¹⁵⁶ Snbandara, *Wikimedia Commons- Phantom 4.jpg*, March 24, 2016, https://commons.wikimedia.org/wiki/File:Phantom_4.jpg.

The next parameters are flight modes and patterns. According to Nex and Remondino, three primary flight modes have been identified. These are manual, assisted, or autonomous.¹⁵⁷ Examples of typical image acquisition overlay are shown in Figure 4.11.

Figure 4.11: Different flight Patterns: a) manual mode, b) low-cost navigation system with irregular image overlap, and c) automated flying and acquisition mode
From Nex and Remondino¹⁵⁸

Option b is not usually performed, as flights are done either by manual acquisition (a) or full automation (including takeoff and landing) (c). UAVs with built in cameras make the manual acquisition very easy, as the user is able to see the view of the UAV through a corresponding tablet and then take their pictures accordingly. This method becomes tiresome when a large amount of data needs to be acquired. Therefore, automated acquisition can be used. Automatic image acquisition can be done through software such as Pix4D or DJI Go apps. Additionally, flights are usually done in linear or circular patterns (Figure 4.12) to capture information to ensure consistent overlap.¹⁵⁹

¹⁵⁷ Nex and Remondino, “UAV for 3D Mapping Applications,” 5.

¹⁵⁸ Ibid.

¹⁵⁹ Aicardi et al., “UAV Photogrammetry with Oblique Images: First Analysis on Data Acquisition and Processing,” 837.

Figure 4.12: Flight path patterns- Linear Pattern (left) and circular pattern (right)
From Aicardi et al.¹⁶⁰

A complementary step to the image acquisition process is the taking of control points on site. This is done through a traditional surveying method of using a total station. These control points are then captured in the photographs taken by the UAV in order to properly align and scale the object of interest for digital reconstruction.

Since UAVs are equipped with Global Navigation Satellite Systems (GNSS) technology, another option that exists is to combine the photographs solely using that information. This involves registering the photos in photogrammetric software packages based solely off of the GPS coordinates that are logged as part of the exif data from each photograph.

Camera Orientation

From the literature reviewed, there are two types of camera orientations when capturing aerial photographs. These are nadir (camera positioned vertically) and oblique (camera positioned on an angle). Nadir images are used primarily for the creation of Digital Terrain (or Surface) Models.¹⁶¹ Oblique images used to capture photographs of building facades. Especially for systems with built in cameras, oblique images are easy to capture because it only involves adjusting the

¹⁶⁰ Ibid.

¹⁶¹ Ibid., 835.

camera to the desired angle using the remote control. If the camera is not built in, it can be adjusted before each flight. Some research that has been done using oblique images is shown in the articles consulted.¹⁶² These articles help to illustrate how using oblique UAV images can be advantageous in capturing information of an entire building site instead of just capturing the terrain, which was formerly the only available end product.

Data Processing

The processing of UAV acquired photographs is done using traditional photogrammetric software packages. The guiding question behind acquiring data is how it can be integrated and registered with information collected by terrestrial documentation techniques (terrestrial photogrammetry and laser scanning). Point clouds created through either 3D laser scanning or terrestrial photogrammetry can be used as a comparison to the point cloud created by UAV photogrammetry to validate the results. This concept was explored in numerous articles consulted and the general conclusion made was that the UAV point cloud model was comparable in accuracy.¹⁶³

¹⁶² These articles used oblique images as a part of their image capturing methodology: Aicardi et al., “UAV Photogrammetry with Oblique Images: First Analysis on Data Acquisition and Processing”; W. Ostrowski, “Accuracy of Measurements in Oblique Aerial Images for Urban Environment,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-2-W2 (TC IV
 11th 3D Geoinfo Conference (Volume XLII-2-W2) - 20–21 October 2016, Athens, Greece, Copernicus GmbH, 2016), 79–85, doi:10.5194/isprs-archives-XLII-2-W2-79-2016; Anand Vetrivel et al., “Identification of Damage in Buildings Based on Gaps in 3D Point Clouds from Very High Resolution Oblique Airborne Images,” *ISPRS Journal of Photogrammetry and Remote Sensing* 105 (July 2015): 61–78, doi:10.1016/j.isprsjprs.2015.03.016.

¹⁶³ These articles both compared point clouds taken with UAV photogrammetry to those of laser scanning or terrestrial photogrammetry, as well as describing how the data sets can be integrated together: Aicardi et al., “UAV Photogrammetry with Oblique Images: First Analysis on Data Acquisition and Processing”; Bolognesi et al., “Testing the Low-Cost RPAS Potential in 3D Cultural Heritage Reconstruction”; Bolognesi et al., “Accuracy of Cultural Heritage 3D Models by RPAS and Terrestrial Photogrammetry”; Hashim et al., “Integration of Low Altitude Aerial & Terrestrial Photogrammetry Data in 3D Heritage Building Modeling.”

Software Comparison

The most common software used to process the images according to the literature reviewed was Agisoft PhotoScan. One article published by Aicardi et al. in 2016 tested the results of using different photogrammetric software packages to process a data set.¹⁶⁴ That group used 190 images, taken by a Sony ILCE-5100 camera.¹⁶⁵ Figure 4.14 below is a summary chart of the number of millions of points created using each respective software. This type of comparison is very beneficial to see which software is able to best handle oblique UAV images in regards to the point density of the created model for visualization and further dissemination purposes. A high quality setting in each was used to come up with the final results. Additional software comparisons are displayed in articles by Yanagi and Chikatsu, and Niederheiser et al.¹⁶⁶

Table 4.4 Dense Point Cloud Comparison

Adapted from Aicardi et al.¹⁶⁷

Dense Point Cloud Comparison							
	Agisoft Photoscan Professional	Pix4D	3Df Zephyr	MicMac	SURE	ContextCapture	VisualSFM
Number of Points (Millions)	3.5	4.4	<1	4	7.5	19	<1

¹⁶⁴ Aicardi et al., “UAV Photogrammetry with Oblique Images: First Analysis on Data Acquisition and Processing.”

¹⁶⁵ Ibid., 837.

¹⁶⁶ H. Yanagi and H. Chikatsu, “Performance Evaluation of 3D Modelling Software for UAV Photogrammetry,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLI-B5 (XXIII ISPRS Congress, Commission V (Volume XLI-B5) - 12-19 July 2016, Prague, Czech Republic, Copernicus GmbH, 2016), 147–52, doi:10.5194/isprs-archives-XLI-B5-147-2016; Robert Niederheiser et al., “Deriving 3D Point Clouds from Terrestrial Photographs- Comparison of Different Sensors and Software,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLI-B5 (XXIII ISPRS Congress, Commission V (Volume XLI-B5) - 12-19 July 2016, Prague, Czech Republic, Copernicus GmbH, 2016), 685–92, doi:10.5194/isprs-archives-XLI-B5-685-2016.

¹⁶⁷ Aicardi et al., “UAV Photogrammetry with Oblique Images: First Analysis on Data Acquisition and Processing,” 839.

Gaps in Current Literature

There were two predominant gaps identified in the literature reviewed on UAVs. The first has to do with the need for expanded education in regards to UAVs, whereas the second is in relation to the SFOC process.

In “Integrating UAVs into Geomatics Curriculum,” Al-Tahir argued that as UAVs are becoming more available for commercial purchase, there is a lack of training courses about using them correctly.¹⁶⁸ Al-Tahir proposes three alternatives: a design project, a short module in a course, or a complete advanced course in UAV photogrammetry.¹⁶⁹

UAV photogrammetry is based on equipment in regards to the funds available to purchase both hardware and software components. A course could use off the shelf low cost UAVs, or those that are modular and can be customized. The one constant is that whatever UAV is used should have a high degree of usability.

The SFOC process is one that should also be modified. Cultural heritage practitioners, ideally those working for the Federal Government, should speak with Transport Canada about creating a process to streamline the SFOC application for their work. Additionally, Transport Canada should look into creating a uniform SFOC template for all of their respective regions to follow. These can be separate forms for both lower cost and weight UAVs (less than 1kg), as well as those that weight more than 1kg. This could also help to speed up the processing for these

¹⁶⁸ R. Al-Tahir, “Integrating UAV into Geomatics Curriculum,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-1-W4 (International Conference on Unmanned Aerial Vehicles in Geomatics, 30 Aug–02 September 2015, Toronto, Canada, Copernicus GmbH, 2015), 387–90, doi:10.5194/isprsarchives-XL-1-W4-387-2015.

¹⁶⁹ Ibid. To expand on these three alternatives, the design project can be similar to the Capstone that Carleton University does during the fourth year of engineering undergraduate degrees. The short module can be a few lectures in specific courses about cultural heritage documentation, such as CIVE 3207: Historic Site Recording or ARCN 4900: Directed Reading at Carleton University. A whole course in UAV photogrammetry can include detailed photogrammetric processing and hands on training.

applications since all forms will be of the same nature, making it easier for Transport Canada officials to process.

4) Laser Scanning

The final digital documentation technique examined here is laser scanning. Böhler and Marbs state that a laser scanner is “any device that collects 3D co-ordinates of a given region of an object’s surface automatically and in a systematic pattern at a high rate achieving the results in near real time.”¹⁷⁰ This definition has been adapted by Grussenmeyer et al., in *3D Recording, Documentation and Management of Cultural Heritage*, to describe the act of laser scanning as “an active, fast and automatic acquisition technique using laser light for measuring, without any contact and in a dense regular pattern, 3D coordinates of points on surfaces.”¹⁷¹ The outcome of a laser scanning survey is the generation of a point cloud. Colours can be associated with each of the points if the scanner contains a built-in camera feature. As the technique revolves around the use of lasers to collect measurements, the act of laser scanning can be described as a range-based recording technique.

Types of Scanners

There are three different types of laser scanners: triangulation based, time of flight, and phase based.¹⁷² Each type of scanner has its own benefits and constraints, and it is up to the cultural heritage practitioner to choose the best equipment depending on the nature of the job at hand.

¹⁷⁰ Wolfgang Boehler and Andreas Marbs, “3D Scanning Instruments,” *Proceedings of the CIPA WG 6* (2002): 1.

¹⁷¹ Pierre Grussenmeyer et al., “Chapter 6- Basics of Range-Based Modelling Techniques in Cultural Heritage 3D Recording,” in *3D Recording, Documentation and Management of Cultural Heritage* (Dunbeath: Whittles Publishing, 2016), 305, <http://site.ebrary.com/lib/oculcarleton/docDetail.action?docID=11276440.305>.

¹⁷² Historic England, “3D Laser Scanning for Heritage | Historic England,” 7.

As the name suggests, triangulation based scanners capture measurements through “triangulating the position of a spot or stripe of laser light.”¹⁷³ Their field of view is limited, and as such, this type of setup is best suited for capturing very detailed measurement of smaller objects or artifacts located in close proximity to the scanner, within 15-30cm.¹⁷⁴ The objects are usually placed on a turntable, which is revolved with each scan. These types of laser scanners can also be of the handheld variety as well. Some common examples of triangulation based scanners are the Nextengine 3D Laser Scanner and the Creaform Handyscan 3D.¹⁷⁵

Time of Flight scanners use a methodology that involves measuring the time it takes for the laser pulse to bounce off of the object and then return back to the scanner. Based off of knowing that the speed of light is a constant, the scanner is able to determine the distance to the object. The basic principle of this technique is illustrated in Figure 4.13. These types of scanners have a very high accuracy at long distances, resulting in an accuracy of a few millimeters at a scanning distance hundred meters.¹⁷⁶ Some examples of Pulse Based scanners are the Leica P40, Riegl VZ 2000 and Trimble TX8.¹⁷⁷

Figure 4.13: Time of flight concept illustration
By author

¹⁷³ Ibid., 7–8.

¹⁷⁴ Grussenmeyer et al., “Chapter 6- Basics of Range-Based Modelling Techniques in Cultural Heritage 3D Recording,” 318.

¹⁷⁵ Nextengine.com, “NextEngine 3D Laser Scanner,” accessed July 12, 2017, <http://www.nextengine.com/products>; Leonard inc, “Portable 3D Scanners for 3D Scanning | HandySCAN 3D by Creaform,” accessed July 12, 2017, <https://www.creaform3d.com/en/metrology-solutions/portable-3d-scanner-handyscan-3d>.

¹⁷⁶ Grussenmeyer et al., “Chapter 6- Basics of Range-Based Modelling Techniques in Cultural Heritage 3D Recording,” 313–14.

¹⁷⁷ Ibid.

The final type of scanner category is phase based. These types of scanners send out laser waves and measure the distance between the phase shifts in the sent and returning wave. This concept is visually described in Figure 4.14, as the blue colour represents the wave leaving scanner, while the grey colour represents the wave returning to the scanner, with the distance between them being described as a phase shift.

Figure 4.14: Phase based concept illustration
By author

Because of the continuous nature of the wave, the scanner is able to capture a larger amount of points on average than phase based scanners, which creates a denser point cloud.¹⁷⁸ Examples of this type of scanner include the Faro Focus3D X330 and the Trimble FX.¹⁷⁹ They have a very wide field of view, with the Faro Focus3D X330 having a 360 degree horizontal view and 300 degree vertical view as seen in Figure 4.15.

¹⁷⁸ Historic England, “3D Laser Scanning for Heritage | Historic England,” 8.

¹⁷⁹ Grussenmeyer et al., “Chapter 6- Basics of Range-Based Modelling Techniques in Cultural Heritage 3D Recording,” 316.

Figure 4.15: Faro Focus3D X330 Scanner field of view
From Faro Technologies Inc.¹⁸⁰

Table 4.5 illustrates the basic principles of each type of scanner, along with its optimal operating range and accuracy.

Table 4.5: Comparison of Laser scanner types

Adapted from Historic England and Grussenmeyer¹⁸¹

Type of Scanner	Use	Typical Accuracy/Operating Range	Rate of Capture
Triangulation	Scan small objects. Scan surfaces.	50 microns/0.1m-1m (max)	50,000 to 1M pts/sec
Time of Flight	Survey building facades/interiors	3mm-6mm at a ranges up to a few hundred meters	21,000 to 1M pts/sec
Phase Shift	Survey building facades/interiors	5mm at ranges of 50-100m	200,000 to 1.2M pts/sec

Laser Scanning Survey Planning and Record Keeping

When conducting the laser scan survey, it is important to remember to plan ahead for the survey to reduce possible errors while on site. If that is not possible, good practice is to do an initial walkthrough of the site and mark down on a site plan where potential surveying positions should be. This minimizes the number of station setups, thereby saving time while working on site.

¹⁸⁰ FARO Technologies Inc., "FARO Laser Scanner Focus3D X330 Manual," February 2015, 4.

¹⁸¹ Historic England, "3D Laser Scanning for Heritage | Historic England," 7; Grussenmeyer et al., "Chapter 6- Basics of Range-Based Modelling Techniques in Cultural Heritage 3D Recording," 311–20.

An additional topic relates to the concept of good record keeping of project information.

Historic England recommends that the following metadata be kept to go along with any scanning project:

- File name
- Date of capture
- Scanning system used
- Monument name
- Scan number (unique scan number for this survey)
- Total number of points
- Point density on the object (with reference range)¹⁸²

As also explained in the photogrammetry section, point density is a very important attribute to consider when laser scanning. This is because the point density governs the types of results that can be produced, as if features cannot be seen in a point cloud, then they cannot be interpreted.

Table 4.6 displays approximate point densities for objects at various sizes.

Table 4.6: Point density values for feature sizes
Adapted from Historic England¹⁸³

Feature Size	Example of Feature	Point density needed to give 66% probability feature will be visible	Point density required to give 95% probability that feature will be visible
10m	Large earth work	3500mm	500mm
1m	Small earth work/ditch	350mm	50mm
100mm	Large stone masonry	35mm	5mm
10mm	Tool markings	3.5mm	0.5mm
1mm	Weathered masonry	0.35mm	0.05mm

Based on the Faro Focus3D X330, the scanner available to use for this thesis research, the point densities vary based on the settings of the scanner. This scanner was used in this thesis research because I had permission to operate it from Professor Mario Santana. On the scanner itself, the density is described as the point distance (in millimetres) at a distance of 10m. Therefore, depending on the final end result, the practitioner can change the scanner settings to get a higher or lower density.

¹⁸² Historic England, “3D Laser Scanning for Heritage | Historic England,” 15.

¹⁸³ Ibid, 10.

There are drawbacks to scanning, such as the fact that anything the scanner cannot see will not appear in the generated point cloud, the relative optimal distance of the scanner to the object (in case of dangerous areas), and that the viewpoints for the scanner may not be optimal for capturing information.¹⁸⁴ As a solution to this issue, laser scanning can always be supplemented with more scanning positions or photogrammetric point clouds.

Data Processing

When laser scanners operate, their end product is known as a raw scan. In order to turn these raw scans into point cloud files, the data has to be registered using additional software. Faro scanners use a software called SCENE, and Leica uses Cyclone.¹⁸⁵ As these are proprietary software, this is an additional cost that conservators must incur in order to use this recording technique. An important point to note is that when both processing and viewing point cloud data, powerful computers are required. Though the term powerful is arbitrary, Table 4.7 helps to illustrate the system requirements for using Faro Scene.

Table 4.7: Faro SCENE system requirements

Adapted from¹⁸⁶

	Minimum Requirements (10 scans or less)	Recommended
Processor	Intel Core i7- 4 physical cores	Intel Core i7/Xeon- 8 physical cores
Video Card	OpenGL 4.1, 2GB Memory	OpenGL 4.1, 4GB Memory, NVIDIA Quadro
RAM	16 GB	64GB
Hard Drive	256 GB Solid State Drive	512 GB Solid State Drive and Regular HDD
Operating System	Windows 7, 8, 8.1, 10 (64-bit)	Windows 7, 8, 8.1, 10 (64-bit)
Screen Resolution	1366x768	1920x1080

¹⁸⁴ Arianna Pesci et al., “A Laser Scanning-Based Method for Fast Estimation of Seismic-Induced Building Deformations,” *ISPRS Journal of Photogrammetry and Remote Sensing* 79 (May 2013): 186, doi:10.1016/j.isprsjprs.2013.02.021.

¹⁸⁵ FARO Technologies Inc., “FARO Laser Scanner Software - SCENE - Overview,” accessed July 6, 2017, <http://www.faro.com/en-us/products/faro-software/scene/overview>; Leica Geosystems, “Leica Cyclone - 3D Point Cloud Processing Software - Leica Geosystems - HDS,” accessed July 14, 2017, http://hds.leica-geosystems.com/en/leica-cyclone_6515.htm.

¹⁸⁶ FARO Technologies Inc., “FARO Laser Scanner Software - SCENE - System Requirements,” accessed July 14, 2017, <http://www.faro.com/en-us/products/faro-software/scene/system-requirements#main>.

The purpose of using this software is to register (or combine) the raw scans together so they can be exported as a point cloud. As each individual scan contains its own local coordinate system, registration is required to bring all of the scans into the same project coordinate system, usually established by total station control points.¹⁸⁷ The final registered point clouds can then be exported into a variety of formats, including LAS, e57, RCS, and asci in order to be further developed into more useful end products like meshes, orthophotos, or BIM models.

To summarize, Figure 4.16 illustrates a typical workflow of the laser scanning process.

Figure 4.16: Laser scanning workflow
From Historic England¹⁸⁸

Chapter Summary

This chapter provided an overview of the methodological background behind the digital recording techniques that were used in the case study sites. It described how the total station was

¹⁸⁷ Historic England, “3D Laser Scanning for Heritage | Historic England,” 12.

¹⁸⁸ Ibid., 11.

used to establish a general coordinate system of the site to reference the photogrammetric and laser scanning surveys. The chapter also detailed photogrammetric principles and the general workflow when using Agisoft PhotoScan; the primary photogrammetric processing software in the case study processing. In regards to laser scanning, the importance of point density and survey planning were discussed.

Chapter 5: Diagnosis of Data for Conservation

Introduction

The goal of this section is to explore the state of the arts in relation to deliverables that can be generated with the data collected during the digital recording stage. By knowing what can be produced, conclusions can be made to determine which outcomes are acceptable/useful for each case study.

Two central themes have been identified to categorize the explored literature. Management of Sites is the first theme. It will encompass three main areas of research: a) Building Information Modelling (BIM), b) structural health monitoring, and c) structural analysis. Building Information Modelling is the creation of as-found products that accurately depict the current state of the building and its individual systems in a three-dimensional environment. For structural health monitoring, an in-depth look at the ways in which recording can be used for implementing long-term monitoring strategies at historic places is discussed. Structural analysis will be looking into how data captured through digital recording processes is being used to aid in the analysis of geometrically complex historic sites.

The second theme is Dissemination and Sharing of Data. This track encompasses ways in which collected information is presented to both the public and fellow researchers in regards to gaining a stronger understanding of the historic place through the concept of digital immersion. This is examined here through the use of: a) digital heritage inventories and b) virtual reality technology.

1) Management of Sites

a) Building Information Modelling (BIM)

The first topic to be discussed is Building Information Modelling (BIM). According to The National Building Information Model Standard Project Committee, BIM is “a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.”¹⁸⁹ BIM represents a fundamental shift in how building design and management has been approached, as it moves from traditional 3D CAD models to a tool that now incorporates two more dimensions- time and cost.¹⁹⁰ These two added dimensions aid in the decision making processes of a project because of how information contained in a BIM can be easily shared between all project partners. BIM represents a building in a more “semantically rich manner” because it provides intelligence to building elements.¹⁹¹ Building intelligence in this manner refers to the fact that instead of drawing two parallel lines to represent walls like in AutoCAD, BIM models a wall as a single object that includes its internal geometry like is displayed in real life. These building components (walls, windows, doors, columns, etc.) are stored in pre-defined object libraries in the software, and are easily customizable in relation to not only their geometry, but other parameters such as weight, density and material cost.¹⁹² Additionally, each of the objects in a BIM environment have a set of pre-established rules

¹⁸⁹ National Institute of Building Sciences, “Frequently Asked Questions About the National BIM Standard-United States™ | National BIM Standard - United States,” 2016, <https://www.nationalbimstandard.org/faqs>.

¹⁹⁰ S. Logothetis, A. Delinasiou, and E. Stylianidis, “Building Information Modelling for Cultural Heritage: A Review,” in *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-5-W3 (25th International CIPA Symposium 2015 (II-5/W3) - 31 August-4 September 2015, Taipei Taiwan, Copernicus GmbH, 2015), 178, doi:10.5194/isprsannals-II-5-W3-177-2015.

¹⁹¹ Pingbo Tang et al., “Automatic Reconstruction of as-Built Building Information Models from Laser-Scanned Point Clouds: A Review of Related Techniques,” *Automation in Construction* 19, no. 7 (November 1, 2010): 830, doi:10.1016/j.autcon.2010.06.007.

¹⁹² Logothetis, Delinasiou, and Stylianidis, “Building Information Modelling for Cultural Heritage,” 178.

that govern them. For example, walls should connect with other walls, floors, and ceilings, and that windows and doors are to be placed within walls.¹⁹³ Common BIM software includes Autodesk Revit, ArchiCAD, Bentley Architecture, and Google SketchUpPro.¹⁹⁴

Figure 5.1 illustrates how BIM relies on a continual process of planning, designing, building, and managing.¹⁹⁵ BIM for new construction relies mostly on the planning, designing, and building stages, as there is no maintenance/refurbishment yet required for the site.¹⁹⁶ Contrastingly, BIM for existing buildings relies on the management aspect of the lifecycle. This is because documenting buildings aids in conservation initiatives to help gain a better understanding of the resource at hand.

Figure 5.1: BIM cyclical process
From Logothetis¹⁹⁷

¹⁹³ Tang et al., "Automatic Reconstruction of as-Built Building Information Models from Laser-Scanned Point Clouds," 831.

¹⁹⁴ Logothetis, Delinasiou, and Stylianidis, "Building Information Modelling for Cultural Heritage," 179.

¹⁹⁵ Ibid., 178.

¹⁹⁶ Rebekka Volk, Julian Stengel, and Frank Schultmann, "Building Information Modeling (BIM) for Existing Buildings — Literature Review and Future Needs," *Automation in Construction* 38 (March 1, 2014): 110, doi:10.1016/j.autcon.2013.10.023.

¹⁹⁷ Logothetis, Delinasiou, and Stylianidis, "Building Information Modelling for Cultural Heritage," 178.

HBIM

Historic Building Information Modelling (HBIM) is the process of using uniquely designed building elements based off of as-built conditions or historic data, for the creation of a BIM.¹⁹⁸ Khodeir et al. describes it as “a system for modelling historic structures from laser scanning and photogrammetric data.”¹⁹⁹ This definition resonates best with this work because of the main focus on digital recording techniques. As BIM was not specifically designed as a tool for modelling existing structures, there has been much research in the field on how HBIM procedures can be implemented for cultural heritage resources containing complex geometries. The general workflow as seen in much of the literature explored revolved around the following three steps: Data Collection, Data Processing, and BIM.²⁰⁰

The data collection phase focuses primarily on the techniques used to capture the data. The use of laser scanning is the most popular because of the amount of information the scans capture

¹⁹⁸ M. Murphy, E. McGovern, and S. Pavia, “Historic Building Information Modelling- Adding Intelligence to Laser and Image Based Surveys,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XXXVIII-5-W16 (WG V/4
4th ISPRS International Workshop 3D-ARCH 2011: “3D Virtual Reconstruction and Visualization of Complex Architectures” (Volume XXXVIII-5/W16) - 2-4 March, Trento, Italy, Copernicus GmbH, 2012), 1, doi:10.5194/isprsarchives-XXXVIII-5-W16-1-2011.

¹⁹⁹ Laila M. Khodeir, Dalia Aly, and Shaimaa Tarek, “Integrating HBIM (Heritage Building Information Modeling) Tools in the Application of Sustainable Retrofitting of Heritage Buildings in Egypt,” *Procedia Environmental Sciences*, Improving Sustainability Concept in Developing Countries (ISCDC), 34 (January 1, 2016): 263, doi:10.1016/j.proenv.2016.04.024.

²⁰⁰ The workflows examined come from the following resources: Tang et al., “Automatic Reconstruction of as-Built Building Information Models from Laser-Scanned Point Clouds”; Volk, Stengel, and Schultmann, “Building Information Modeling (BIM) for Existing Buildings — Literature Review and Future Needs”; L. Barazzetti et al., “BIM from Laser Clouds and Finite Element Analysis: Combining Structural Analysis and Geometric Complexity,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5-W4 (WG V/4, CIPA
 3D-Arch 2015 – 3D Virtual Reconstruction and Visualization of Complex Architectures (XL-5/W4) - 25–27 February 2015, Avila, Spain, Copernicus GmbH, 2015), 345–50, doi:10.5194/isprsarchives-XL-5-W4-345-2015; Fabrizio Banfi, “Building Information Modelling—A Novel Parametric Modeling Approach Based on 3D Surveys of Historic Architecture,” in *Euro-Mediterranean Conference* (Springer, 2016), 116–27; S. Fai, M. Filippi, and S. Paliaga, “Parametric Modelling (BIM) for the Documentation of Vernacular Construction Methods: A BIM Model for The Commissariat Building, Ottawa, Canada,” in *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-5-W1 (TC V
 XXIV International CIPA Symposium (Volume II-5/W1) - 2-6 September 2013, Strasbourg, France, Copernicus GmbH, 2013), 115–20, doi:10.5194/isprsannals-II-5-W1-115-2013.

in a limited time frame. UAVs can be used as well, as seen in Themistocleous et al.²⁰¹ The data processing stage involves the registering of scans/images into point cloud formats that can be used for the BIM stage. This also involves cleaning the point clouds by removing unwanted data. The stage that is of greatest interest in this section is the BIM itself and of the various strategies used to model complicated geometries.

HBIM Modelling Procedures and Approaches

In order to develop BIM from existing point cloud data, geometric modelling approaches are required. These can range from the object detection level, like beams and columns, up to more complex assemblies such as vaults. The key factor in recent literature is determining ways to model these elements using algorithms in order to cut down on modelling time.²⁰²

One strategy seen in research for modelling the entirety of the structure is through the use of NURBS.²⁰³ NURBS is a type of mathematical model that fits smooth curves (splines) to a

²⁰¹ K. Themistocleous, A. Agapiou, and D. Hadjimitsis, “3D Documentation and BIM Modelling of Cultural Heritage Structures Using UAVs: The Case of The Foinikaria Church,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-2-W2 (TC IV
 11th 3D Geoinfo Conference (Volume XLII-2/W2) - 20–21 October 2016, Athens, Greece, Copernicus GmbH, 2016), 45–49, doi:10.5194/isprs-archives-XLII-2-W2-45-2016.

²⁰² These resources examine object identification algorithms: Andrey Dimitrov and Mani Golparvar-Fard, “Segmentation of Building Point Cloud Models Including Detailed Architectural/Structural Features and MEP Systems,” *Automation in Construction* 51 (March 2015): 32–45, doi:10.1016/j.autcon.2014.12.015; Frédéric Bosché et al., “The Value of Integrating Scan-to-BIM and Scan-vs-BIM Techniques for Construction Monitoring Using Laser Scanning and BIM: The Case of Cylindrical MEP Components,” *Automation in Construction*, 30th ISARC Special Issue, 49 (January 1, 2015): 201–13, doi:10.1016/j.autcon.2014.05.014; Lucía Díaz-Vilariño et al., “Automatic Detection and Segmentation of Columns in As-Built Buildings from Point Clouds,” *Remote Sensing* 7, no. 11 (November 20, 2015): 15651–67, doi:10.3390/rs71115651; Livio De Luca and David Lo Buglio, “Geometry vs Semantics: Open Issues on 3D Reconstruction of Architectural Elements,” 2014, 36–49, doi:10.1007/978-3-662-44630-0_3.

²⁰³ These articles illustrate NURBS approaches for BIM: D. Oreni et al., “Survey Turned into HBIM: The Restoration and the Work Involved Concerning the Basilica Di Collemaggio after the Earthquake (L’Aquila),” in *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-5 (ISPRS Technical Commission V Symposium (Volume II-5) - 23-25 June 2014, Riva del Garda, Italy, Copernicus GmbH, 2014), 267–73, doi:10.5194/isprsannals-II-5-267-2014; Banfi, “Building Information Modelling—A Novel Parametric Modeling Approach Based on 3D Surveys of Historic Architecture”; Luis Javier Sánchez-Aparicio et al., “Photogrammetric, Geometrical, and Numerical Strategies to Evaluate Initial and Current Conditions in Historical Constructions: A Test Case in the Church of San Lorenzo (Zamora, Spain),” *Remote Sensing* 8, no. 1 (January 13, 2016): 60, doi:10.3390/rs8010060; Bing SONG et al., “Reconstructing DEM Using TLS Point Cloud Data and NURBS

surface based on governing control points (point cloud boundaries).²⁰⁴ NURBS allows for these complex geometries to be turned into BIM elements. This is shown in Figures 5.2 and 5.3, as basic boundaries are first generated from an existing point cloud, and then more NURBS curves are applied to the model in order to generate surfaces. Barazzetti et al., describes how NURBS surfaces can then be turned into intelligent objects containing defined relationships and attributes such as thickness and materiality— characteristics essential for the BIM.²⁰⁵

Figure 5.2: Point cloud to NURBS
From Barazzetti²⁰⁶

Figure 5.3: Enhanced NURBS curves transformed to surface
From Barazzetti²⁰⁷

Surface,” *Transactions of Nonferrous Metals Society of China* 25, no. 9 (September 1, 2015): 3165–72, doi:10.1016/S1003-6326(15)63947-4.

²⁰⁴ Tang et al., “Automatic Reconstruction of as-Built Building Information Models from Laser-Scanned Point Clouds,” 834.

²⁰⁵ L. Barazzetti et al., “Creation of Parametric BIM Objects from Point Clouds Using Nurbs,” *The Photogrammetric Record* 30, no. 152 (December 1, 2015): 341, doi:10.1111/phor.12122.

²⁰⁶ Ibid., 348.

²⁰⁷ Ibid., 351.

Level of Detail and Development

One difficulty that is posed during the modelling process is establishing how detailed the model should be. As a point cloud contains points at millimetre (or submillimetre) accuracies, it enables the generation of very accurate models. This presents a huge time cost and investment, as drawing every brick in a wall may be sufficient for some projects, but not relevant for others. Therefore, to combat this problem a central set of standards are needed to quantify this concept. One of the most common systems referenced is the level of development or detail (LoD) system created by BIM Forum.²⁰⁸ This system is split into five LoD steps as seen in the table below:

Table 5.1: Level of Detail

Adapted from BIM Forum²⁰⁹

LOD 100	Not representative of the object being modeled. Relates more to information/symbols attached to the object, but nothing about size, shape, or location.
LOD 200	Elements act as placeholders by showing the basic shape for users to interpret
LOD 300	Elements contain the correct size, shape, location and orientation. Measurements can be taken from the object.
LOD 400	Elements contain enough detail that they can be manufactured or installed on site.
LOD 500	As-built and field verified measurements of building elements.

For heritage based projects, Dore and Murphy note that it is challenging to establish a set of standards because of the overall complexity and irregular nature of these buildings.²¹⁰ This therefore puts an emphasis on the quality of results garnered from the digital recording of these sites, because a highly detailed point cloud has the ability to accurately display these complex

²⁰⁸ BIM Forum, “2016 Level of Development Specification,” 2016, 12.

²⁰⁹ Ibid.

²¹⁰ Conor Dore and Maurice Murphy, *Chapter 7- Historic Building Information Modelling (HBIM) in Handbook of Research on Emerging Digital Tools for Architectural Surveying, Modeling, and Representation*, ed. Stefano Brusaporci, Advances in Geospatial Technologies Book Series (Hershey, PA: Engineering Science Reference, 2015), 234.

geometries. Fai and Rafeiro reiterate this point by stating: “much of the capacity to model higher LoD in existing buildings relies on how it has been documented rather than the capacity of the modelling program to create complex geometries.”²¹¹

One strategy for working with LoD in historic buildings is presented by Banfi.²¹² The aim of this work was to integrate different LoDs in the BIM depending on the component/element being examined. This was implemented at the Basilica of Collemaggio in L’Aquila, where areas that lacked point cloud data were modelled at LOD 200, whereas the models of the interior displayed each individual stone and were characterized at LOD 500.²¹³

BIM for Management of Sites

As explained, BIM serves as a very useful tool for the management of sites through its use of intelligent building elements. It provides an efficient way to organize information about sites. Further, different iterations of the site throughout time can be generated within the same BIM, examined explored by Fai et al., 2011 through their Batawa Project.²¹⁴ Fassi et al. propose another type of facility management strategy through an online platform called BIM3DSG.²¹⁵ Using BIM as a base, the software allows users to view complex 3D models online, share information that is

²¹¹ S. Fai and J. Rafeiro, “Establishing an Appropriate Level of Detail (LoD) for a Building Information Model (BIM)-West Block, Parliament Hill, Ottawa, Canada,” in *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-5 (ISPRS Technical Commission V Symposium (Volume II-5) - 23-25 June 2014, Riva del Garda, Italy, Copernicus GmbH, 2014), 127, doi:<https://doi.org/10.5194/isprsannals-II-5-123-2014>.

²¹² Banfi, “Building Information Modelling—A Novel Parametric Modeling Approach Based on 3D Surveys of Historic Architecture.”

²¹³ Ibid., 122–23.

²¹⁴ Fai et al., “Building Information Modelling and Heritage Documentation.”

²¹⁵ F. Fassi et al., “A New Idea of BIM System for Visualization, Web Sharing and Using Huge Complex 3D Models for Facility Management,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5-W4 (WG V/4, CIPA </br> 3D-Arch 2015- 3D Virtual Reconstruction and Visualization of Complex Architectures (XL-5/W4) - 25-27 February 2015, Avila, Spain, Copernicus GmbH, 2015), 359–66, doi:[10.5194/isprsarchives-XL-5-W4-359-2015](https://doi.org/10.5194/isprsarchives-XL-5-W4-359-2015).

linked to the model, and be able to keep track of any changes made to the building through the use of tablets on site.²¹⁶

b) Structural Health Monitoring

The second area of focus with respect to site management is structural health monitoring.

This term is defined as:

The process of implementing a damage identification strategy... This process involves the observation of a structure or mechanical system over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of system health.²¹⁷

The use of digital recording techniques presents a way in which such observations can be documented— specifically through the use of point clouds. It is a longer term strategy for conservation of historic places, as the results of one round of observation are compared to those taken in the past, also known as a ‘multi-temporal’ strategy.

The first aspect of structural health monitoring involves the concept of deformation analysis, specifically in regards to monitoring and planning for it. Deformation modelling is considered to be “the systematic measurement and tracking of the alteration in the shape or dimensions and position of an object as a result of the application of stress to it.”²¹⁸ Digital recording techniques have the possibility to aid in this endeavor due to their ability to capture large amount of data, while at the same time providing a non-intrusive strategy- particularly useful in unsafe or dangerous areas such as after earthquakes or other natural disasters.

²¹⁶ Ibid.

²¹⁷ Charles R. Farrar and Keith Worden, “An Introduction to Structural Health Monitoring,” *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 365, no. 1851 (2007): 304.

²¹⁸ W. Mukupa et al., “A Review of the Use of Terrestrial Laser Scanning Application for Change Detection and Deformation Monitoring of Structures,” *Survey Review* 49, no. 353 (March 4, 2017): 100, doi:10.1080/00396265.2015.1133039.

Though published more than ten years ago, “A New Approach for Health Monitoring of Structures: Terrestrial Laser Scanning” is still an important resource in regards to establishing the use of laser scanning for deformation monitoring.²¹⁹ The study compared the deformation results of a test involving the use of a concentrated load applied to a simply supported beam using accelerometers, strain gauges, linear variable differential transformer (LVDTs), and laser scanning. The scanning results were compared to the LVDTs, as they were the most accurate, and discovered that the maximum deflections were “less than 1mm and within 1.6% of those measured directly by LVDT.”²²⁰ It is important to note that the former three measuring techniques are intrusive, as they must be applied directly to the object of interest, whereas laser scanning is non-intrusive and will not harm the object of interest.

As laser scanning technologies have progressed over the last number of years, so have strategies used for the detection of deformations in structures. Recent scholarship on point cloud comparison methodologies illustrate this concept in greater detail.²²¹ In particular, these involve either one of two strategies: point to point (also known as point-wise or cloud to cloud) or point to surface (also referred to as object-oriented) comparisons.

²¹⁹ H. S. Park et al., “A New Approach for Health Monitoring of Structures: Terrestrial Laser Scanning,” *Computer-Aided Civil and Infrastructure Engineering* 22, no. 1 (2007): 19–30, doi:10.1111/j.1467-8667.2006.00466.x.

²²⁰ Ibid., 30.

²²¹ Articles examining point cloud comparison methodologies: Shen, Lindenberg, and Wang, “Change Analysis in Structural Laser Scanning Point Clouds”; R. C. Lindenberg, “Trends in Detecting Changes from Repeated Laser Scanning Data,” in *Proceedings of the 2nd Joint International Symposium on Deformation Monitoring (JISDM), Nottingham (UK), 9-11 Sept. 2013; Preprint* (University of Nottingham, 2013); Roderik Lindenberg and Peter Pietrzyk, “Change Detection and Deformation Analysis Using Static and Mobile Laser Scanning,” *Applied Geomatics* 7, no. 2 (2015): 65–74; Mukupa et al., “A Review of the Use of Terrestrial Laser Scanning Application for Change Detection and Deformation Monitoring of Structures”; Arianna Pesci, Giuseppe Casula, and Enzo Boschi, “Laser Scanning the Garisenda and Asinelli Towers in Bologna (Italy): Detailed Deformation Patterns of Two Ancient Leaning Buildings,” *Journal of Cultural Heritage* 12, no. 2 (April 1, 2011): 117–27, doi:10.1016/j.culher.2011.01.002; Pesci et al., “A Laser Scanning-Based Method for Fast Estimation of Seismic-Induced Building Deformations”; Arianna Pesci, Giordano Teza, and Enzo Boschi, “Laser Scanning-Based Detection of Morphological Changes of a Historical Building Occurred during a Seismic Sequence: Method and Case Study,” *International Journal of Geomatics and Geosciences* 5, no. 3 (2015): 427.

As the name suggests, a point to point comparison compares the distances between individual points in two different point clouds. The point clouds must be registered to one another to ensure that they are in the same local coordinate system.²²² This is done by referencing each model to the same control points; if this is not the case, alternate strategies can be employed. The open source software CloudCompare has a manual registration process whereby reference points are selected in each point cloud to perform the registration.²²³ Once in the same reference system, the points on each cloud are then directly compared to one another by calculating their Euclidean distance as seen in Figure 5.4.²²⁴ The difficulty in this method is that it is nearly impossible for two point clouds taken at different time periods to have the exact points.²²⁵ Point densities may vary between the two data sets, and there is potential for propagation of registration errors between the point clouds. It is not considered to be the best methodology, but is possible depending on the data collection methodologies followed.²²⁶

Figure 5.4: Point to Point Comparison
From Shen²²⁷

²²² Shen, Lindenberg, and Wang, "Change Analysis in Structural Laser Scanning Point Clouds," 2.

²²³ CloudCompare.org, "Alignment and Registration," accessed July 11, 2017, http://www.cloudcompare.org/doc/wiki/index.php?title=Alignment_and_Registration.

²²⁴ Shen, Lindenberg, and Wang, "Change Analysis in Structural Laser Scanning Point Clouds," 10.

²²⁵ Mukupa et al., "A Review of the Use of Terrestrial Laser Scanning Application for Change Detection and Deformation Monitoring of Structures," 100.

²²⁶ Ibid.

²²⁷ Shen, Lindenberg, and Wang, "Change Analysis in Structural Laser Scanning Point Clouds," 10.

The next approach is the point to surface comparison. In this case, a mathematical primitive (planes, spheres, cylinders) modeled by a triangular mesh, is applied to the object of interest depending on its geometry.²²⁸ The least squares principle is used to apply the primitive. One of the point clouds is represented by the surface primitive (usually the base point cloud) onto which the new point cloud point distances are compared to.²²⁹ This methodology presents a more accurate way of comparing multi-temporal point clouds, as this base primitive can be saved and directly applied to future data collections for ease of comparison. Functions in CloudCompare such as ‘Fit Plane,’ and ‘Fit 2D Polygon’ can be used for the creation of these primitives.²³⁰

Figure 5.5: Point to surface based principle
From Shen²³¹

As a subsection to surface based comparisons is a concept called morphological maps.²³²

What differentiates morphological maps from the base point to surface methodology is the fact

²²⁸ Ibid.

²²⁹ Mukupa et al., “A Review of the Use of Terrestrial Laser Scanning Application for Change Detection and Deformation Monitoring of Structures,” 109.

²³⁰ CloudCompare.org, “Fit 2D Polygon,” accessed July 11, 2017,

http://www.cloudcompare.org/doc/wiki/index.php?title=Fit_2D_Polygon; CloudCompare.org, “Fit Plane,” accessed July 11, 2017, http://www.cloudcompare.org/doc/wiki/index.php?title=Fit_Plane.

²³¹ Shen, Lindenbergh, and Wang, “Change Analysis in Structural Laser Scanning Point Clouds,” 11.

²³² Morphological maps are discussed in these articles: Pesci, Casula, and Boschi, “Laser Scanning the Garisenda and Asinelli Towers in Bologna (Italy)”; Pesci, Teza, and Boschi, “Laser Scanning-Based Detection of Morphological Changes of a Historical Building Occurred during a Seismic Sequence: Method and Case Study”; Pesci et al., “A Laser Scanning-Based Method for Fast Estimation of Seismic-Induced Building Deformations”; Lindenbergh and Pietrzyk, “Change Detection and Deformation Analysis Using Static and Mobile Laser Scanning”; E. Bonali et al., “Deformation of Ancient Buildings Inferred by Terrestrial Laser Scanning Methodology: The Cantalovo Church Case Study (Northern Italy)*,” *Archaeometry* 56, no. 4 (August 1, 2014): 703–16, doi:10.1111/arc.12028.

that it is “hypothetically representing a previous not altered state of the investigated object.”²³³ Therefore, they are primarily used after major damages have occurred to places of interests, such as post-earthquake analysis. The one possible drawback to this technique is actually defining the ‘primitive’ to be used, as it must be representative of how the building looked before the damages. Additionally, the primitive used is influenced by the individual doing the analysis.²³⁴ Pesci et al., recommends that more than one data collection session should be conducted (if possible) and the fact that current conditions of critical infrastructure should be studied as to pre-plan for potential seismic activity to establish a baseline record of these important buildings.²³⁵ Taking this methodology a step further is Quagliarini et al., who used RANSAC Shape Detection algorithm in their work to identify a series of primitives (planes, cylinders, and spheres) based on the shapes contained in the construction element of interest.²³⁶ Using these primitives, both deformation maps and horizontal and vertical cross sections were created. In regards to the RANSAC method, CloudCompare has a free plugin available for this analysis.²³⁷

One final note of analysis is that there was one case study by Lee et al. to measure the displacement of columns that did not use either of the two base methodologies.²³⁸ Instead, the authors established a datum line along the center of the column of interest, and compared the

²³³ Lindenbergh and Pietrzyk, “Change Detection and Deformation Analysis Using Static and Mobile Laser Scanning,” 70.

²³⁴ Pesci et al., “A Laser Scanning-Based Method for Fast Estimation of Seismic-Induced Building Deformations,” 198.

²³⁵ Ibid.

²³⁶ Enrico Quagliarini, Paolo Clini, and Mirko Ripanti, “Fast, Low Cost and Safe Methodology for the Assessment of the State of Conservation of Historical Buildings from 3D Laser Scanning: The Case Study of Santa Maria in Portonovo (Italy),” *Journal of Cultural Heritage* 24 (March 2017): 175–83, doi:10.1016/j.culher.2016.10.006.

²³⁷ Ruwen Schnabel, Roland Wahl, and Reinhard Klein, “Efficient RANSAC for Point-Cloud Shape Detection,” *Computer Graphics Forum* 26, no. 2 (June 2007): 214–26; CloudCompare.org, “RANSAC Shape Detection (Plugin),” accessed July 11, 2017, [http://www.cloudcompare.org/doc/wiki/index.php?title=RANSAC_Shape_Detection_\(plugin\)](http://www.cloudcompare.org/doc/wiki/index.php?title=RANSAC_Shape_Detection_(plugin)).

²³⁸ M. C. Lee et al., “Finding the Displacement of Wood Structure in Heritage Building by 3D Laser Scanner,” in *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-5-W3 (25th International CIPA Symposium 2015 (II-5/W3) - 31 August–4 September 2015, Taipei Taiwan, Copernicus GmbH, 2015), 165–69, doi:10.5194/isprsannals-II-5-W3-165-2015.

displacement between point clouds from 2006 and 2013.²³⁹ If the deformation reaches an established critical angle, then the structure will collapse. This methodology does not reference if and how the point clouds were registered, and what the justification was behind using the datum type of methodology. The case study did establish a monitoring program of scanning at three-month intervals. One suggestion is that if they were to use a primitive fit method, the results would have been more accurate, as the authors' values ranged only in centimeter accuracy.²⁴⁰

Another key aspect of structural health monitoring is the concept of condition assessment. In particular, literature examined focused on how digital documentation techniques (namely photogrammetry and laser scanning) could be applied to monitor pathologies in masonry structures. Masonry was chosen as the material of interest because from background research about Prince of Wales Fort and QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen (both sites constructed from/out of masonry), there were pathologies identified that impacted the conservation of these sites. From reviewing site documentation, the state of materials at The Log Farm was in good condition.

The first major masonry deterioration is that of weathering and erosion. Moses et al. explain how terrestrial laser scanning is being applied to measure rock recession by weathering due to the non-contact aspect of the tool, as well as its ability to provide highly precise measurements.²⁴¹ The Micro-Erosion Meter (MEM) is the most widely used instrument to measure surface erosion, but it is a contact-based method.²⁴² Depending on the historical values associated with the object of interest, contact with the surface may not be allowed, which is why laser

²³⁹ Ibid., 168–69.

²⁴⁰ Ibid.

²⁴¹ Cherith Moses, David Robinson, and John Barlow, "Methods for Measuring Rock Surface Weathering and Erosion: A Critical Review," *Earth-Science Reviews* 135 (August 1, 2014): 144–45, doi:10.1016/j.earscirev.2014.04.006.

²⁴² Ibid.

scanning can be used. Moses et al. comments on the fact that laser scanning requires a specialist to operate the equipment, as well as the equipment being very costly and out of the budget constraints of some projects. They advocate for the use of close-range photogrammetry for initial data capture if these constraints occur.²⁴³

An alternative approach is to assess the pathologies based on the point intensity (or pixel) data through image classification procedures.²⁴⁴ By understanding that different pathologies display different emittance properties, damages can be detected by analyzing the individual pixels. The setup involved using a laser scanner to capture infrared data of the object of interest and a camera to capture colour information. They were then merged and first different algorithms were applied to classify the pixels into different classes based on their intensity. These classes would show up as different colours (thereby displaying different intensities) in the final images, allowing conservators to assess the pathologies.²⁴⁵ In Bitelli et al., this strategy was employed to analyze salt crystallization effects on plastered and non-plastered brick masonry.²⁴⁶ This work used a triangulation-based laser scanner, which allowed for sub-millimeter precision.

c) Structural Analysis

The final category of management of sites is Structural Analysis. This section builds off of the previous two, as BIM and structural health monitoring results can be incorporated into or used

²⁴³ Ibid.

²⁴⁴ Beatriz Menéndez, “Non-Destructive Techniques Applied to Monumental Stone Conservation,” 2016, doi:10.5772/62408; Crespo et al., “Damage Detection on Historical Buildings Using Unsupervised Classification Techniques”; Julia Armesto-González et al., “Terrestrial Laser Scanning Intensity Data Applied to Damage Detection for Historical Buildings,” *Journal of Archaeological Science* 37, no. 12 (December 1, 2010): 3037–47, doi:10.1016/j.jas.2010.06.031; Gabriele Bitelli et al., “Salt Effects in Plastered and Unplastered Outdoors Brick Masonry: Quantitative Laser Monitoring of Surface Decay Evolution,” *International Journal of Architectural Heritage* 9, no. 5 (July 4, 2015): 581–93, doi:10.1080/15583058.2013.821542.

²⁴⁵ Crespo et al., “Damage Detection on Historical Buildings Using Unsupervised Classification Techniques,” 186–87.

²⁴⁶ Bitelli et al., “Salt Effects in Plastered and Unplastered Outdoors Brick Masonry.”

directly for the structural analysis of historic sites. The scope of this research is to understand how the data from digital recording techniques has been registered and delivered in a format that can be usable for the development of structural analysis products.

Geometric Modelling and Meshing

After the point cloud has been registered and cleaned, it can then be used for identification of key physical objects or building features through geometrical modelling. According to Walsh et al., this step is considered to be a “prerequisite for structural engineering calculations” because it enables an understanding of basic object geometry.²⁴⁷ Conde-Carneo et al. also iterate the importance of the proper development of geometrical models because they are easier to discretize (division of the model into smaller elements).²⁴⁸ In regards to individual object detection methodologies, Walsh et al., describe a workflow detailing this procedure. After the point clouds are registered, algorithms are applied to them in order to identify sharp feature points, fit surfaces to these points, and finally apply predefined ‘objects’ to them.²⁴⁹ These objects consist of three-dimensional shapes like rectangular prisms, spheres, and cylinders, which can then be used for analysis applications. This is very similar to the fitting of primitives as discussed in the structural health monitoring section.

According to Hinks et al., there are three main ways to generate models for engineering simulation applications— constructive solid geometry, boundary representations (NURBS) and

²⁴⁷ Sara B. Walsh et al., “Data Processing of Point Clouds for Object Detection for Structural Engineering Applications,” *Computer- Aided Civil and Infrastructure Engineering* 28, no. 7 (2013): 497, doi:10.1111/mice.12016.

²⁴⁸ B. Conde-Carnero et al., “Exploitation of Geometric Data Provided by Laser Scanning to Create FEM Structural Models of Bridges,” *Journal of Performance of Constructed Facilities* 30, no. 3 (June 1, 2016), doi:10.1061/(ASCE)CF.1943-5509.0000807.

²⁴⁹ Walsh et al., “Data Processing of Point Clouds for Object Detection for Structural Engineering Applications.”

spatial subdivisions.²⁵⁰ As examined in the BIM review, NURBS procedures can also serve as a way to generate geometrically complex models. The third methodology (spatial subdivision) is the area of interest for this section. The spatial subdivision method involves a cubic grid (also known as octree) based system used to break down the whole building of interest into a series of “nonoverlapping 3D regions, commonly referred to as voxels.”²⁵¹ The way this process works is that the building is first displayed as one voxel, and then broken down into eight smaller subdivisions. There are three classifications of voxels: empty (do not contain detail), full (contain detail), and grey (boundary voxels).²⁵² Shown in Figure 5.6 is a visual representation of the voxel system. The user repeats the voxelization process for the entirety of the model until the voxels reach the specified size.

Figure 5.6: Octree Process
From Truong-Hong²⁵³

²⁵⁰ Tommy Hinks et al., “Point Cloud Data Conversion into Solid Models via Point-Based Voxelization,” *Journal of Surveying Engineering* 139, no. 2 (May 1, 2013): 73, doi:10.1061/(ASCE)SU.1943-5428.0000097.

²⁵¹ Ibid.

²⁵² Ibid.

²⁵³ Linh Truong-Hong and Debra F. Laefer, “Octree-Based, Automatic Building Façade Generation from LiDAR Data,” *Computer-Aided Design* 53 (August 2014): 47, doi:10.1016/j.cad.2014.03.001.

Voxel based model methodologies are examined in Castellazzi et al., which described a new methodology to automate the process of voxel creation for the generation of mesh that can be used for finite element modeling processes.²⁵⁴ The procedure is called *CLOUD2FEM* and involves slicing the 3D point cloud into a series of 2D planes.²⁵⁵ Each plane is analogized to be like a digital image, whereby it is divided into a series of grids (representing pixels) with a user-imputed distance between points. The planes are then stacked on top of each other at that same distance to turn the entire model into voxels. This is illustrated in Figure 5.7.

Figure 5.7: *CLOUD2FEM* Visual representation
From Castellazzi et al.²⁵⁶

²⁵⁴ Articles where voxel methodologies have been employed: Tommy Hinks et al., “Point Cloud Data Conversion into Solid Models via Point-Based Voxelization”; Giovanni Castellazzi et al., “From Laser Scanning to Finite Element Analysis of Complex Buildings by Using a Semi-Automatic Procedure,” *Sensors (Basel, Switzerland)* 15, no. 8 (August 2015): 18360, doi:10.3390/s150818360; Giovanni Castellazzi et al., “An Innovative Numerical Modeling Strategy for the Structural Analysis of Historical Monumental Buildings,” *Engineering Structures* 132 (February 1, 2017): 229–48, doi:10.1016/j.engstruct.2016.11.032; Truong-Hong and Laefer, “Octree-Based, Automatic Building Façade Generation from LiDAR Data.”

²⁵⁵ Castellazzi et al., “An Innovative Numerical Modeling Strategy for the Structural Analysis of Historical Monumental Buildings.”

²⁵⁶ Ibid., 231.

After this stage is complete, the model then has to be transformed into a usable mesh for finite element modelling. As voxels contain eight nodes, the logical choice of meshing is the hexahedral mesh, also composed of eight nodes. This ensures that a mesh can always be generated from the geometric model. Another benefit to using this mesh is that it ensures that the mesh is closed, and therefore does not contain any holes that could negatively impact the finite element model calculation.²⁵⁷

Another type of meshing strategy employed in the literature explored was the use of tetrahedral elements to form the mesh because of the relative ease of generation.²⁵⁸ One possible limitation to this type of mesh is that the final number of elements generated is larger than through the use of other types of mesh, and as such, requires more computer processing power to complete the analysis.²⁵⁹

Finite Element Modelling

Only after the point cloud has been properly established as a mesh model can the final step of the workflow take place— finite element analysis. Finite element analysis involves analyzing the behaviour of the elements in the mesh when loads are applied to them. This process first

²⁵⁷ Ibid., 246.

²⁵⁸ Literature that employs the tetrahedral mesh: B. Conde-Carnero et al., “Exploitation of Geometric Data Provided by Laser Scanning to Create FEM Structural Models of Bridges”; L. Barazzetti et al., “BIM FROM LASER CLOUDS AND FINITE ELEMENT ANALYSIS: COMBINING STRUCTURAL ANALYSIS AND GEOMETRIC COMPLEXITY,” *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5-W4 (February 19, 2015): 345–50, doi:10.5194/isprsarchives-XL-5-W4-345-2015; Luigi Barazzetti et al., “Cloud-to-BIM-to-FEM: Structural Simulation with Accurate Historic BIM from Laser Scans,” *Simulation Modelling Practice and Theory* 57 (September 2015): 71–87, doi:10.1016/j.simpat.2015.06.004; Castellazzi et al., “From Laser Scanning to Finite Element Analysis of Complex Buildings by Using a Semi-Automatic Procedure”; Luis Javier Sánchez-Aparicio et al., “The Combination of Geomatic Approaches and Operational Modal Analysis to Improve Calibration of Finite Element Models: A Case of Study in Saint Torcato Church (Guimarães, Portugal),” *Construction and Building Materials* 70 (November 15, 2014): 118–29, doi:10.1016/j.conbuildmat.2014.07.106.

²⁵⁹ Barazzetti et al., “Cloud-to-BIM-to-FEM,” 77.

involves importing the models into Finite Element Modelling software to perform the analysis. Some common software used in the literature includes ANSYS, and Abaqus.²⁶⁰

Determining the material properties for different groups of elements is an important step before starting the analysis. These can consist of density, Young's modulus, Shear modulus and stresses.²⁶¹ As seen in Barazzetti et al. 2015, after generating these parameters, an iterative approach is used by running a linear-elastic analysis under self-weight while making some assumptions about distributed loads on the model.²⁶² This is done in order to determine if the material assumptions are correct, and that the model experiences the same behaviour (crack patterns) as the current state of the building.²⁶³

In Castellazzi et al., a different type of approach is used whereby the authors identified macro-elements (towers and walls) that were built during different eras in order to simulate the condition of the structure after it had been affected by an earthquake.²⁶⁴ In their structural simulations, connections between the sections have been added in the numerical model to help simulate the behaviour of these areas under linear-static and non-linear analysis simulation.²⁶⁵

2) Dissemination and sharing of data

After all of the documentation is conducted, the question that comes to mind is “what is going to happen to the information?” Guiding Principle 9 by Letellier et al., states that: “dissemination of heritage records should be as wide as possible, and the location of the records

²⁶⁰ ANSYS, “Structures: FEA Simulation | ANSYS,” accessed July 14, 2017, <http://www.ansys.com/products/structures>; Dassault Systèmes, “Abaqus,” accessed July 14, 2017, <https://www.3ds.com/products-services/simulia/products/abaqus/>.

²⁶¹ Castellazzi et al., “An Innovative Numerical Modeling Strategy for the Structural Analysis of Historical Monumental Buildings.”

²⁶² Barazzetti et al., “Cloud-to-BIM-to-FEM,” 80.

²⁶³ Ibid.

²⁶⁴ Castellazzi et al., “An Innovative Numerical Modeling Strategy for the Structural Analysis of Historical Monumental Buildings.”

²⁶⁵ Ibid., 235.

should be made public.”²⁶⁶ Two ways that this can be accomplished have been explored in this research. These are through the use of digital heritage inventories and virtual reality applications.

a) Digital Heritage Inventories

Digital Heritage Inventories can be described as a collection of information about historic places of interest while having a primary focus on accessibility of information to the public realm.

Cimadomo cites three categories of inventories for dissemination. These are through Keyhole Markup Language (KML), Digital Repositories, or Web Based Dissemination Applications.²⁶⁷

KML files are used to display geographic information in mapping based browsers such as Google Earth and Google Maps.²⁶⁸ Base information about sites of interest can be created from free open source GIS software such as QGIS²⁶⁹ and then exported as a KML file to be uploaded into public databases. One drawback to this method is that there is no way for the user wanting to use the information know if it is the most recent iteration of the information.²⁷⁰

Digital Repositories provide a way to share content of archives or collections through a web-based database. This type of inventory does not feature geographical information like interactive maps through the KML format.²⁷¹ One example of a digital repository type of inventory is the Europeana project, which serves as an online inventory for over 1800 museums and archives in Europe.²⁷² There are also free programs available such as Sketchfab and Blender are used to

²⁶⁶ Letellier et al., *Recording, Documentation, and Information Management for the Conservation of Heritage Places. Guiding Principles*, 36.

²⁶⁷ G. Cimadomo, “Documentation and Dissemination of Cultural Heritage: Current Solutions and Considerations about Its Digital Implementation,” in *2013 Digital Heritage International Congress (DigitalHeritage)*, vol. 1, 2013, 555–62, doi:10.1109/DigitalHeritage.2013.6743796.

²⁶⁸ Google, “Keyhole Markup Language,” accessed July 12, 2017, <https://developers.google.com/kml/>.

²⁶⁹ QGIS, “Welcome to the QGIS Project!,” accessed July 12, 2017, <http://www.qgis.org/en/site/>.

²⁷⁰ Cimadomo, “Documentation and Dissemination of Cultural Heritage,” 556–57.

²⁷¹ Ibid., 557–58.

²⁷² Ibid., 557.

display 3D models online, but they are not made specifically for cultural heritage applications.²⁷³ One database examined to display cultural heritage models online is the open source software called 3DHOP (3D Heritage Online Presenter).²⁷⁴ 3DHOP was designed to be used by non-expert developers in order to share highly detailed 3D content (point clouds or meshes) on a standard web page. The usability aspect is most important part of the software, which is complimented by the accessible nature of its website by displaying step by step tutorials.²⁷⁵

Finally, there are Web Based Dissemination Inventories. These are another form of a digital heritage inventory and can be considered as a combination approach of KML and digital repositories, as they revolve both around geospatial information and archival research.²⁷⁶ Two examples have been examined in the reviewed literature: Arches Heritage Inventory Management System and Cultural Diversity and Material Imagination in Canadian Architecture-CDMICA.²⁷⁷

Arches is an open source software geared towards the generation of customizable heritage inventories at both organization and project levels.²⁷⁸ It was developed by the Getty Conservation Institute and World Monuments Fund (WMF) as a tool that is economical, customizable, standards

²⁷³ Blender Foundation, “Blender.org - Home of the Blender Project - Free and Open 3D Creation Software,” *Blender.org*, accessed July 12, 2017, <https://www.blender.org/>; Sketchfab, “Sketchfab - Your 3D Content Online and in VR,” *Sketchfab*, accessed July 12, 2017, <https://sketchfab.com>.

²⁷⁴ Marco Potenziani et al., “3DHOP: 3D Heritage Online Presenter,” *Computers & Graphics* 52 (November 2015): 129–41, doi:10.1016/j.cag.2015.07.001; Visual Computing Lab-ISTI and CNR initiative, “3DHOP - Home,” accessed July 12, 2017, <http://vcg.isti.cnr.it/3dhop/index.php>.

²⁷⁵ Visual Computing Lab-ISTI and CNR initiative, “3DHOP - Home.”

²⁷⁶ Cimadomo, “Documentation and Dissemination of Cultural Heritage,” 558–60.

²⁷⁷ Carleton Immersive Media Studio, “Cultural Diversity and Material Imagination in Canadian Architecture-CDMICA,” accessed July 6, 2017, <http://cims.carleton.ca/#/aboutCdmica>; P. K. Carlisle et al., “The Arches Heritage Inventory and Management System: A Standards-Based Approach to the Management of Cultural Heritage Information,” in *CIDOC (International Committee for Documentation of the International Council of Museums) Conference: Access and Understanding—Networking in the Digital Era, Dresden, Germany*, 2014, 6–11; David Myers, Alison Dalgity, and Ioannis Avramides, “The Arches Heritage Inventory and Management System: A Platform for the Heritage Field,” *Journal of Cultural Heritage Management and Sustainable Development* 6, no. 2 (2016): 213–24; J. Paul Getty Trust and World Monuments Fund, “What Is Arches Software for Cultural Heritage Inventory and Management?,” accessed July 6, 2017, <https://www.archesproject.org/what-is-arches/>; Fai et al., “Building Information Modelling and Heritage Documentation.”

²⁷⁸ Myers, Dalgity, and Avramides, “The Arches Heritage Inventory and Management System: A Platform for the Heritage Field.”

based, easy to use, and accessible.²⁷⁹ In order to accomplish these goals, the software revolves around the management of six resource types:

- Heritage resources (buildings, landscapes)
- Heritage resource groups (urban/rural areas)
- Actors (people, organizations)
- Historical events (floors, earthquakes)
- Activities (conservation interventions)
- Information resources (historical documents, building drawings)²⁸⁰

The way the program works is that it establishes relationships between all of these resources in order to understand how the documentation is interconnected. The Arches framework has been illustrated in the following case studies: Williams describing the Silk Roads in the Kingdom of Bhutan, Jan detailing how it was used in three rural villages in Hualien County in Taiwan, and Carlisle et al., examining the inventory for potential use in English Heritage.²⁸¹

CDMICA is a publically accessible database of twenty heritage buildings from the Canadian Register of Historic Places that have been documented in a BIM environment.²⁸² Information about various construction typologies, construction details, and building typologies are displayed on this database. What makes this resource valuable is that these BIM models, along with building plans, sections, details and bibliographical information, are available for download for free.²⁸³

²⁷⁹ Ibid.

²⁸⁰ Ibid., 217.

²⁸¹ Tim Williams, "Silk Roads in the Kingdom of Bhutan and the Development of a National Heritage Inventory," *Archaeology International* 19, no. 0 (December 12, 2016), doi:10.5334/ai.1918; J. F. Jan, "Digital Heritage Inventory Using Open Source Geospatial Software," in *2016 22nd International Conference on Virtual System Multimedia (VSMM)*, 2016, 1–8, doi:10.1109/VSMM.2016.7863192; P. K. Carlisle and E. S. Lee, "Bringing It All Together: Networking Heritage Inventories in England," in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5-W2 (TC V
 XXIV International CIPA Symposium (Volume XL-5/W2) - 2-6 September 2013, Strasbourg, France, Copernicus GmbH, 2013), 161–63, doi:https://doi.org/10.5194/isprsarchives-XL-5-W2-161-2013.

²⁸² Carleton Immersive Media Studio, "Cultural Diversity and Material Imagination in Canadian Architecture-CDMICA."

²⁸³ Ibid.

Web based systems provide a huge wealth of information and are deemed excellent tools for dissemination of information. The one constraint of using this type of inventory is that they are very complicated to set up. Users setting up the program must have knowledge of computer programming languages, as the coding behind the software is what makes it such an effective tool. Therefore, this type of inventory is directed at expert users to maintain and update the database.

To summarize, Table 5.2 organizes the pros and cons of the three main digital heritage inventory types.

Table 5.2: Summary of Digital Heritage Inventory typologies
Adapted from²⁸⁴

	Pros	Cons
KML	-Easy to use and interpret -No programming knowledge required	-Difficult to update -No consistent database structure -No record of interventions
Digital Repositories	-Large data collection -Can display 3D models -Search engines	-Not used for spatial data (i.e. maps)
Web Based	-Widely Customizable -All in one type of system (combines KML and Digital Repositories) - Open source (free)	-Programming knowledge required for set up

b) Cultural Heritage and Virtual Reality

Virtual Reality (VR) can be described as “a realistic and immersive simulation of a three-dimensional environment, created using interactive software and hardware, and experienced or controlled by movement of the body.”²⁸⁵ Pozzi and Ott describe virtual reality as an example of an “ICT (Information and Communication Technology).”²⁸⁶ This is because ICT’s revolve around

²⁸⁴ Cimadomo, “Documentation and Dissemination of Cultural Heritage.”

²⁸⁵ Dictionary.com Unabridged, “Virtual Reality,” accessed July 14, 2017, <http://www.dictionary.com/browse/virtual--reality>.

²⁸⁶ Francesca Pozzi and Michela Ott, “Towards a New Era for Cultural Heritage Education: Discussing the Role of ICT,” *Computers in Human Behavior*, Social and Humanistic Computing for the Knowledge Society, 27, no. 4 (July 1, 2011): 1365, doi:10.1016/j.chb.2010.07.031.

the principle of ‘discovery when learning’ versus that of rote teaching, thereby presenting an alternate way of communicating information to the public.²⁸⁷

The goal of exploring literature relating to VR in this work is to gain an understanding of how it has been used in the field of cultural heritage. The combination of virtual reality with cultural heritage applications, results in the concept of virtual heritage.²⁸⁸ Roussou describes virtual heritage as encompassing “conservation, reproduction, representation, [and] digital reprocessing” principles.²⁸⁹ Additionally, Sanders states that “virtual heritage works as eyecandy” with respect to engaging users with cultural heritage concepts.²⁹⁰ The way users are able to interact with these historic places is unlike any other type of experience, and as such, this new tool presents another way to disseminate information.

The virtual reality environment is generated in what is known as a cyberspace.²⁹¹ Kalay and Marx 2006, detail four types of cyber environments that are based around principles of developing places in the physical world. These include:

- Hyper-reality Cyberspaces: created as a perfect recreation of the physical environment;
- Abstracted reality Cyberspaces: still resemble the physical environment but not exactly;

²⁸⁷ Ibid., 1367.

²⁸⁸ R. M. Reffat and E. M. Nofal, “Effective Communication with Cultural Heritage Using Virtual Technologies,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5-W2 (TC V
 XXIV International CIPA Symposium (Volume XL-5/W2) - 2-6 September 2013, Strasbourg, France, Copernicus GmbH, 2013), 519, doi:10.5194/isprsarchives-XL-5-W2-519-2013.

²⁸⁹ Maria Roussou, “Virtual Heritage: From the Research Lab to the Broad Public,” *Bar International Series* 1075 (2002): 93.

²⁹⁰ Donald H. Sanders, “Why Do Virtual Heritage,” *Archaeology Magazine*, 2008, 435.

²⁹¹ Yehuda E. Kalay and John Marx, “Architecture and the Internet: Designing Places in Cyberspace,” *First Monday*, 2005.

- Hybrid Cyberspaces: combination of physical and virtual environment, as users can walk through walls for example;
- Virtual spaces: has its own set of rules as to how the user experiences the space, in the sense that the rules governing the above types of cyberspace do not exist.²⁹²

Within these environments, Folgieri organizes the level of interaction and engagement under one of two categories: passive or interactive.²⁹³ Passive environments are those in which users can only navigate and view the spaces, while interactive environments allow users the ability to engage with the space and thereby interact with it.²⁹⁴ Each interaction category can in turn fall under different levels of user immersion, which can be broken down into:

- Non-immersive: computer applications user acts only as the viewer and is able to navigate the virtual space like with virtual tours;
- Semi-immersive: the use of larger monitors/screens onto which the virtual environment is projected onto;
- Immersive: allows the user to experience the virtual environment through the use of headset devices.²⁹⁵

In order to create and access these virtual environments, two main variables are required: software and hardware. The software aspect involves the use of game engines to develop the environments. Game engines are software designed for the development of video games.²⁹⁶ To

²⁹² Ibid.

²⁹³ Raffaella Folgieri, "VR for Cultural Heritage Valorization: A Communication Problem," *Proceedings of Electronic Imaging & The Visual Arts. Firenze, Italy*, 2011, 146–51.

²⁹⁴ Ibid.

²⁹⁵ Ibid.

²⁹⁶ T. P. Kersten, F. Tschirschwitz, and S. Deggim, "Development of a Virtual Museum Including a 4D Presentation of Building History in Virtual Reality," in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-2-W3 (TC II & CIPA 3D Virtual Reconstruction and Visualization of Complex Architectures - 1-3 March 2017, Nafplio, Greece, Copernicus GmbH, 2017), 361, doi:10.5194/isprs-archives-XLII-2-W3-361-2017.

take this concept a step further, ‘serious’ game engines are software used for the development of game designs that have “a non-entertainment goal” such as for educational purposes.²⁹⁷ Vasudevamurt and Uskov detail a comprehensive analysis of serious game engines by comparing them based on factor such as graphics, programming experience, and overall workflow.²⁹⁸ They came to the conclusion that the best game engines for academic purposes are either Unreal Engine 4 or Unity. Malashniak detailed the pros and cons of both Unreal Engine 4 and Unity, two of the most popular game engines used for commercial applications, which are shown in the table below:

Table 5.3: Unity vs Unreal Engine 4
Adapted from²⁹⁹

	Pros	Cons
Unity	<ul style="list-style-type: none"> -Good for creating mobile games -More archival information through forum boards -Easy to work with 	<ul style="list-style-type: none"> -Lower graphics quality than Unreal Engine -Slower scene rendering
Unreal Engine 4	<ul style="list-style-type: none"> -Good for users without a programming background -Open source -Very high quality compared to Unity 	<ul style="list-style-type: none"> -Not recommended for small games -Not as many experts to help with questions, as with Unity

In terms of hardware, the most important aspect of the VR experience is the headset. Greenwald provides a review of the most common headsets available on the market today, which includes the Sony PlayStation VR, HTC Vive, Oculus Rift, and Samsung Gear VR.³⁰⁰ From explored literature, Kersten et al. used the HTC Vive, whereas Gonizzi Barsanti et al., used the Oculus Rift.³⁰¹

²⁹⁷ V. B. Vasudevamurt and A. Uskov, “Serious Game Engines: Analysis and Applications,” in *2015 IEEE International Conference on Electro/Information Technology (EIT)*, 2015, 440–45, doi:10.1109/EIT.2015.7293381.

²⁹⁸ Ibid.

²⁹⁹ Mariana Malashniak, “Unity vs. Unreal: How to Choose the Best Game Engine,” *N-iX*, August 2, 2016, <https://n-ix.com/unity-vs-unreal-choose-best-game-engine/>.

³⁰⁰ Will Greenwald, “The Best VR (Virtual Reality) Headsets of 2017,” *PCMag.com*, June 22, 2017, <https://www.pcmag.com/article2/0,2817,2500286,00.asp>.

³⁰¹ Kersten, Tschirschwitz, and Deggim, “Development of a Virtual Museum Including a 4D Presentation of Building History in Virtual Reality”; S. Gonizzi Barsanti et al., “3D Visualization of Cultural Heritage Artefacts

Virtual Reality environment

Roussou details some key factors for creating virtual reality experiences for the public. These include aspects such as ensuring an interactive experience, generating photorealistic environments, ensuring a high degree of usability, and being relatively inexpensive.³⁰² For the creation of models to be viewed in VR experiences, Kersten et al., discusses the concept of data reduction for the virtual reality application.³⁰³ This is because the number of polygons in the generated mesh models is too high for the VR game engines, and as such, must be reduced. Gonizzi Barsanti et al., also described this issue, as when the models were generated from PhotoScan, the number of triangles were reduced in order to have “lighter models with a high-resolution texture.”³⁰⁴ This methodology ensures that the models can be interpreted from the game engine software, and as such, be displayed in the virtual environment. One final note that must be taken into consideration when designing VR environments is that of user experience. As pointed out in tests done by Gonizzi Barsanti et al., some of the users felt nauseous after using the Oculus Rift, which is a common feeling brought on by low-resolution display.³⁰⁵ Therefore, any system used must be thoroughly tested before being accessed by the public.

The final topic is that of goals of the virtual reality experience. Literature has been consulted to examine some of the outcomes created from using virtual reality. Kersten et al. created a virtual reality environment of The Selimiye Mosque in Edrine, Turkey that allows users to

with Virtual Reality Devices,” in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XL-5-W7 (25th International CIPA Symposium 2015 (XL-5/W7) - 31 August-4 September 2015, Taipei, Taiwan, Copernicus GmbH, 2015), 165–72, doi:10.5194/isprsarchives-XL-5-W7-165-2015.

³⁰² Roussou, “Virtual Heritage: From the Research Lab to the Broad Public.”

³⁰³ Kersten, Tschirschwitz, and Deggim, “Development of a Virtual Museum Including a 4D Presentation of Building History in Virtual Reality,” 363.

³⁰⁴ Gonizzi Barsanti et al., “3D Visualization of Cultural Heritage Artefacts with Virtual Reality Devices,” 168.

³⁰⁵ Ibid., 171.

experience the site without ever seeing the building in person.³⁰⁶ Deggim et al., created a virtual reality 3D reconstruction of the Siegesburg, a castle located in Germany that was destroyed in 1644, based off of historical documentation. The relevance of this application is that it allows the user to experience a site that hasn't existed in the physical realm for hundreds of years.³⁰⁷ Finally, Gonizzi Barsanti describes how VR was used in order to visualize and interact with ancient Egyptian artifacts. This application allows for VR to be used for educational applications, such as in a museum, thereby allowing the visitors to experience the site from a different perspective.³⁰⁸

Chapter Summary

This chapter provided a comprehensive review of potential end-products that can be created from base documentation captured on site through the digital heritage recording techniques. The main organizational structures of these products is either for management of sites (BIM, structural health monitoring, and structural analysis) or dissemination and sharing of data (digital heritage inventories and virtual reality). It was important to emphasize the possible deliverables because some of these end products were produced for the case study sites, including: BIM for the Log Farm, a deformation analysis of Prince of Wales Fort, and a virtual reality application for KV62: Tomb of Tutankhamen.

³⁰⁶ Kersten, Tschirschwitz, and Deggim, "Development of a Virtual Museum Including a 4D Presentation of Building History in Virtual Reality."

³⁰⁷ S. Deggim et al., "The Return of the Siegesburg-3D-Reconstruction of a Dissappeared and Forgotten Monument," in *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-2-W3 (TC II & CIPA- 3D Virtual Reconstruction and Visualization of Complex Architectures (Volume XLII-2/W3) - 1-3 March 2017, Nafplio, Greece, Copernicus GmbH, 2017), 209–15, doi:<https://doi.org/10.5194/isprs-archives-XLII-2-W3-209-2017>.

³⁰⁸ Gonizzi Barsanti et al., "3D Visualization of Cultural Heritage Artefacts with Virtual Reality Devices."

Phase 3: Documentation in Practice

Chapter 6: Research Methodology

Introduction

The research methods in this thesis are of quantitative nature, specifically examining the problem statement through the use of case studies. To reiterate, the problem statement speaks about the need for the optimization of recording methodologies to be used in the generation of outcomes useful to the heritage engineering community, while focusing on the ability to easily disseminate that information. To overcome this problem statement, four case study sites were examined because of their characteristics in allowing for the three stages of research examination to take place (optimization of recording methodologies, interpretation and analysis of collected information, and dissemination of information). The approach taken is based off of that of Demas, whose values based conservation planning methodology discusses the interrelationship between those three stages the collection of information, assessment and analysis, and decision making processes.³⁰⁹ This is organized in Figure 6.1 below.

³⁰⁹ Martha Demas, “Reading 64- Planning for Conservation and Management of Archaeological Sites: A Values-Based Approach (2000),” in *Archaeological Sites: Conservation and Management*, ed. Sharon Sullivan and Richard Mackay, Readings in Conservation (Los Angeles: Getty Conservation Institute, 2013), 653–75.

Figure 6.1: Planning Process Methodology
Adapted from Demas³¹⁰

Case Study Selection and Research Gaps

The case studies were selected because they were available to document at the time of research, and also had qualifications that contributed to answering the initial research questions that form the problem statement. As these main questions rely on the correct capturing and processing of data at their fundamental core, the four case study sites — differing in scope, analysis, and generated outcomes — help to illustrate the fact that not all techniques can be used at each site and the constraints of each site dictate the eventual method of recording used. Though

³¹⁰ Ibid.

there were some similarities between the sites, the challenges encountered at each location were completely different. A strong emphasis was also placed on understanding how the survey data was processed in order to generate these final products, because if the data is not presented in a usable format, these analysis and interpretation stages cannot occur.

The Log Farm

The way in which this site was chosen was because of the established partnership between Professor Mario Santana and Ryan Orr; the Log Farm site custodian. The site served already served as a case study site for Professor Mario Santana's class "CIVE 3207– Historic Site Recording" and after further examination during a site, it presented itself as a feasible case study for this research. Due to its private nature, it was an optimal location for being able to test out digital recording techniques without any disturbances by the public. The project goals for the Log Farm documentation relate to research gaps 4 (the concepts of BIM for heritage conservation projects) and 6 (dissemination of collected information). These goals were established based off of a values-based analysis of the site, with respect to the main character defining element of preserving the visitor experience. The most important part of the research was developing a methodology to document the farm for posterity record keeping as a way of continuing the memory of the farm within the local community, and not for any specific monitoring/analysis deliverables.

Prince of Wales Fort

The involvement with the Prince of Wales Fort documentation project was due to a correspondence between Christian Ouimet, a conservation technologist from Heritage Conservation Services–Public Services and Procurement Canada, and Professor Mario Santana, in May 2016. Christian Ouimet's email described an opportunity for one of the NSERC CREATE students to come to Prince of Wales Fort to perform documentation work of the Fort. Specifically,

the Heritage Conservation Services–Public Services and Procurement Canada, was looking at using the Prince of Wales Fort project as a test case for documenting National Historic Sites through UAV photogrammetry. The project goals for the Fort relate to research gaps 1 and 2. These gaps speak about further analysis of information gathered from digital recording processes, and the role of UAVs within cultural heritage documentation, respectively. The further analysis aspect relates to how the information can be used for structural health monitoring applications; a very relevant topic to this site as it has been greatly affected by climate change. The UAV image acquisition relates to research gap 2. The information collected from these images can then be used for the monitoring applications outlined in research gap 1.

QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen

The inclusion of the documentation of QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen in this research was because of a partnership between Professor Mario Santana and the Getty Conservation Institute. Being able to work at a site of “outstanding universal value” presented an opportunity to detail the methodologies used on site for research purposes.³¹¹ The main objective during the mission was to capture the current state of the conservation of the tombs, specifically in regards to the decorated surfaces. It was an interdisciplinary effort, as the team from Carleton University worked in partnership with members of the Getty Conservation Institute and the Egyptian Ministry of Antiquities. One important note is that all images used here may not be reproduced without the permission of the Getty Conservation Institute. The work from this documentation initiative helped to answer Research Gaps 1, 5, and 6, which speak about how products from digital documentation recording processes can be used for further analysis, how

³¹¹ UNESCO World Heritage Centre, “The Criteria for Selection.”

software can be adapted for heritage conservation applications, and the effective dissemination of information to the public or fellow researchers, respectively.

Team Roles

Three of the four case study sites involved an interdisciplinary effort, encompassing a variety of team members. Therefore, it is important to distinguish the difference between information that was provided to me, and information produced as a part of this research.

The Log Farm

The work produced for this case study was done by myself. Though graduate and undergraduate students in the architectural conservation program at Carleton University did aid in the data acquisition phases on-site, they did not contribute to the data processing stage

Prince of Wales Fort

For this case study, the control point information came from John Gregg and Shawn Kretz, two of the project team members from the Heritage Conservation Services–Public Services and Procurement Canada, who did their own terrestrial photogrammetric survey of the Fort.

QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen

This project was an interdisciplinary effort between Carleton University (Professor Mario Santana, Christian Ouimet, and myself) and Getty Conservation Institute team members. The following deliverables were identified:

- High Resolution Orthophotos
- Floor plan of the tombs
- Cross section(s) of the tombs
- Three-dimensional models of the tombs

Of these outcomes, my involvement and research is primarily focused on the first deliverable—the creation of high resolution orthophotos. My role on-site was as a secondary photographer and documentation support team member, aiding Christian Ouimet (the primary photographer). After returning from the mission, my role involved data processing, image colour correction, and generation of sheet layouts, as described in Chapter 9. In regards to the data used for this case study site, raw photographs and registered laser scans were provided to me by Professor Mario Santana. During the data processing stage in Canada, the high quality of the results being produced with respect to the photogrammetric modelling enabled for another research goal to be identified: The creation of a digitally assisted condition mapping application through the use of virtual reality technology. This application showcases the decorated wall surfaces of the Tomb of Tutankhamen to aid in the conservation initiative from the Getty Conservation Institute.

Equipment and Software Used

Due to a working partnership with Carleton Immersive Media Studio (CIMS), I had access to a variety of equipment to be used for the documentation of the case study sites. It is important to note that this equipment dictated the scope of the research. The following hardware was available for use at each case study site:

Table 6.1: Case Study Equipment used

Case Studies	Equipment used from CIMS
The Log Farm	Leica TS06 Total Station, Leica surveying tripods, Faro Focus3D X330 Laser Scanner
Prince of Wales Fort	DJI Phantom 4 UAV
QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen	Leica TS06 Total Station, Leica surveying tripods, Faro Focus3D X330 Laser Scanner, Nikon D800 DSLR Camera, Ricoh theta camera

The software that was available from CIMS included:

- Adobe Photoshop CS6
- CloudCompare

- Faro SCENE
- Agisoft PhotoScan
- Bentley ContextCapture
- Unreal Engine4
- AutoCAD 2017
- Autodesk ReCap Pro

The computer used to process all of the information was in CIMS and had 32GB of RAM and a 900GB hard drive, which meant that they were higher than the minimum values required for running Faro SCENE software as seen in Table 4.7.

Cost Factor

The equipment used brings up the question of cost. This cost factor can be both of monetary value as well as time cost to perform the work, which were considered during the recording process.

Monetary Cost

In terms of monetary cost, this is twofold: the cost of the equipment (hardware and software) and the cost of transportation to the case study sites. The most expensive equipment used were the Faro Focus3D X330 Laser Scanner and Leica TS06 Total station. They were approximately \$50,000CAD and \$20,000CAD respectively, as described to me by Professor Mario Santana. Therefore, these are not considered to be low-cost recording tools. They were used to document the case study sites because they were available to me during the course of this research, and the fact that they were integral towards completing the projects at QV66 and KV62. The low cost aspect comes in the form of the Phantom 4 UAV, as that was approximately \$2000CAD, which is low cost when compared to the total station and laser scanner. The software cost aspect was another factor to consider, as the software used was available because of licensing agreements with Carleton Immersive Media Studio. If I would have had to buy these software packages individually, it would be very costly. In terms of the case study sites, as the Log Farm was local,

there was minimal cost involved with transportation. For both Prince of Wales Fort and QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen, there was a considerable financial cost involved in the transportation to the sites from the flights, as well as accommodation costs in Churchill, and Luxor.

Time cost

For the Log Farm site, time cost can be considered low because of the site availability and it was within driving distance of Carleton University (approximately 20 kilometres away). If additional site visits were required to capture more information, they were easily booked with the site custodian. Site visits were conducted over the course of twelve weeks from September to December 2016 to familiarize myself with the architecture of the property, identify buildings of interest to be recorded, and to conduct the recording survey.

The recording in Churchill came with a very high time cost, as the team was only on site for three days (August 9-11, 2016). This meant that time had to be maximized on site, and the documentation strategy planned accordingly. When on site, the weather dictated working patterns. If the winds were greater than 32 km/h (the max wind speed that the Phantom 4 can fly it), then flights could not be conducted. Additionally, if there was any sign of rain, flying could not commence.

The mission in Egypt also had a high time cost, as the team had ten working days to document both tombs (March 4-14), with the work at QV66: Tomb of Nefertari encompassing seven days, and KV62: Tomb of Tutankhamen, three days. It was integral to plan out the documentation strategy before leaving Canada to maximize time spent on site. We were informed of the poor lighting conditions in the tombs before leaving for the project, which allowed for ample time to plan out a variety of photography lighting strategies.

Technical Framework

The background information regarding the theory of the digital recording techniques is seen in Chapter 4 of the literature review. The practical, more hands-on training required for the operation and successful use of the equipment used will be described here.

Faro Focus3D X330 Laser Scanner and Faro SCENE Software

In October 2015, a Faro Scanning Training day was conducted by Cansel; a surveying equipment retailer.³¹² This training course provided information about how use both the Faro Focus3D X330 and Faro SCENE software. This course proved to be very helpful in regards to understanding how to properly operate the scanner, setting up a scanning project, choosing the correct scanner settings, and registration of the raw scan data.

UAV Flight Training

It was essential to learn how to fly UAVs and develop this skill set before flying in Churchill, as I had never flown a UAV before. A training session was set up in July 2016 with Professor Jeremy Laliberte, Associate Professor in Mechanical and Aerospace Engineering at Carleton University. The two-day training course helped to establish basic flight principles and provided many opportunities to test out both the Phantom 4, as well as smaller UAVs that did not have GPS stabilization. Flying with smaller UAVs was important in order to gain an understanding of how UAV controllers operate, and because if the UAV were to lose GPS signal, I would know how to safely maneuver the drone back to the ground. From observation when flying, the Phantom 4 had a high degree of usability, and the controller had specific buttons for capturing aerial images and video. The Pix4D application was also experimented with, as a sample flight test was

³¹² Cansel.ca, “About Us, Our History and Our Timeline,” accessed September 14, 2017, <https://www.cansel.ca/en/about-us>.

conducted with the software. Difficulties were experienced when doing this, as the UAV did not return back to the programmed home position after capturing all of the images, and instead dropped to the ground at the location of the last picture it took. This proved to be problematic because it landed in an area of tall grass, which affected the propellers. Therefore, this app was not used when flying on-site and instead only the DJI Go app was used to control the UAV.

Chapter Summary

This chapter highlighted the research methodology involved with the case study sites, focusing on why the case study sites were chosen for this research, and the roles of the project team members and myself at each case study site. This was important to distinguish, because I did not capture all of the information for all of the case study sites. Cost factors were also described in regards to the technology used (hardware and software), and how those tools had an impact in the recording and data processing stages. Finally, technical capacity was discussed in terms of supplementary training required in order to operate the equipment and software.

Chapter 7: The Log Farm

Introduction

From a local context, the first case study is an example of the vernacular architecture of the Ottawa area. The Log Farm, located in Nepean, Ontario, is a reminder of the rich history of early 19th century life in the Ottawa Valley. The site itself consists of a 19th century farmhouse, called the Bradley House, a hay barn, and smaller animal coops and sheds. To re-iterate, the project goals for The Log Farm documentation relate to research gaps 4 and 6, which relate to the concepts of BIM for heritage conservation projects, and the dissemination of collected information.

Site History

As the site itself is leased from the National Capital Commission (NCC), there were many resources available pertaining to the history of The Log Farm Site and how it has evolved over time. The general timeline of the site can be displayed as two distinct categories- pre and post NCC Greenbelt holdings purchase. The pre-NCC purchase is best displayed in a timeline (Figure 7.1) to show the information. It has been adapted from the *Preliminary Development Concept- The Log Farm*, published by the National Capital Commission in 1976.³¹³ From the timeline, the most prominent owners of the land were the Bradley family — Irish immigrants to Canada in the early 1800s.³¹⁴ Their farm prospered due to the timber trade, and then from raising livestock.³¹⁵

³¹³ 1976 Log Farm Preliminary Development Concept

³¹⁴ Martha A. Latta and National Capital Commission, “The Log Farm Site- BhFw-2” (Canada, 2008).

³¹⁵ National Capital Commission, “Bradley Family History” (Canada, n.d.).

Pre 1800's	• Natural Forest Land used by native peoples of Ottawa Valley
1783	• Land acquired under "Crawford Purchase"
1835	• Log Farm first settled by Irish immigrant John Bennett
1842	• First census shows Bennet as land owner
1852	• Bennet registered the land with the Crown
1854	• Property sold to Abraham Bradley
1857	• Log house Built
1916	• Property sold to John Bompas
1966	• Land purchased by NCC as part of their Greenbelt holdings

Figure 7.1: Log Farm site history up to 1966
Adapted from National Capital Commission AE.0:7³¹⁶

The Post-NCC purchase is where most of the relevance of the historical information lies. In 1971, a decision was made in order to conserve the log house at the site because of its relevance of being the last log house in the Greenbelt.³¹⁷ Additionally, the land around the house was preserved because it was one of the last maple bushes in the western part of the Greenbelt.³¹⁸ This decision set in motion the development of land concept plans, and conservation initiatives for the house on the site.

The most pertinent piece of information that was discovered is the fact that the current condition of the house today is not original. In 1975, a project team from Algonquin College was put in place to conserve the house. The conservation action that they chose to implement was that

³¹⁶ National Capital Commission, "AE.0:7 The Log Farm," July 2, 1976, 719; National Capital Commission, "Preliminary Development Concept- The Log Farm" (Canada, 1976).

³¹⁷ National Capital Commission, "BB5.25- The Log Farm" (Canada, n.d.).

³¹⁸ Ibid.

of restoration. Their ideology was to restore the house to the timeframe in which members of the Bradley family inhabited the house, which corresponds to the 1860's.³¹⁹

The rationale behind this decision was because of the “irreversible alterations which have been made in the window and door positions, as well as the weathered condition of the exterior facades.”³²⁰ Some of the major alterations that were done to the house during the duration of the project include:

- Conversion of an existing open concept floor plan to a partitioned floor plan;
- Added 10x10x24' beam set on vertical logs to support the house;
- Added second beam on south side supporting 3 cross-joists;
- Built partition wall between the kitchen and parlour;
- Installed new windows;
- Repointed mortar from interior and exterior foundation.³²¹

The act of restoration is not considered to be the best choice of action because of one of the key points discussed in *Preliminary Development Concept-The Log Farm*. Specifically, the document states “in presenting it to the public the preservation of that experience is more important than an exact restoration of the property.”³²² Therefore, a better approach to have taken would have been preservation instead. This aspect of preservation of experience served as a guiding principle in my own documentation of the site, as this represented a very important character defining element about the property. For the purposes of preserving the house for vernacular architecture information, I decided to concentrate recording and modelling efforts on the Bradley House in

³¹⁹ Glen Furgeson, “AE.15a-A. Merriam-Interior Design Proposal Log House,” June 9, 1976.

³²⁰ Ibid.

³²¹ Doug Stewart and Michelle McMillan, “AE.15aThe Log Farm Project- Summer 1975” (Canada: National Capital Commission, n.d.).

³²² National Capital Commission, “Preliminary Development Concept- The Log Farm.”

particular. Because the surrounding farm buildings and topography of the immediate landscape represent a piece of that visitors experience notion, this is why they were also included as a part of the laser scan survey. In 1976, another intervention occurred in order to finish the work started in 1975 by completing the interior spaces of the house. This intervention was shown in measured drawings of the site found in the NCC archives.³²³

Ryan Orr and his family currently run the site. The primary focus of the site is around giving guests “a sense of what day to day life was like for the Bradley family. That may be a casual self-guided “tour through time” to just enjoy the sights and sounds of the farm animals and see all the different building on the homestead.”³²⁴ Additional programming also includes hands-on experiences of the day to day farm life, a sugar bush, fall harvest, and weekly farmers markets.³²⁵

QGIS Maps of The Log Farm

Using QGIS, maps were created of the site in order to provide context to the site in its surrounding environment (Figures 7.2 and 7.3). Aerial photographs downloaded from the Carleton University GIS Website served as the base layer for the map.³²⁶

³²³ G Furgeson, “1976 Log Farm Restoration Project- Index of Drawings,” May 10, 1976.

³²⁴ thelogfarm.com, “About- The Log Farm,” January 9, 2016, <https://thelogfarm.com/about/>.

³²⁵ Ibid.

³²⁶ Carleton University, “Aerial Images | MacOdrum Library,” accessed July 7, 2017, <https://library.carleton.ca/find/gis/aerial-images>.

Figure 7.2: Context map of The Log Farm site generated in QGIS
Created by author

Figure 7.3: Site scale map of The Log Farm
Created by author

Identified Heritage Values

The site is not designated as heritage, but due to it being one of the last existing log houses in the greenbelt, its conservation is merited.³²⁷ In regards to architectural value, its vernacular style contributes to an understanding of early Ottawa log house construction. It also exhibits social value for being a place that brings the Nepean community together to both experience and interact with the farm like The Bradley family did in the 1860s. Finally, it showcases historical value because even though the house is not in its original state, the overall preservation of the 1860s farming culture is exhibited. The character-defining elements of the site identified by the author are shown below:

- “The preservation of that experience is more important than an exact restoration of the property”³²⁸
- The setting of the farm as being a rural experience in an urban landscape (Figure 7.4)
- Dovetail joinery with chinking (Figure 7.5)
- Heavy timber log construction
- Fieldstone foundation (Figure 7.6)
- Cedar shake shingles (Figure 7.7)

³²⁷ National Capital Commission, “BB5.25- The Log Farm.”

³²⁸ National Capital Commission, “Preliminary Development Concept- The Log Farm.”

Figure 7.4: Rural nature of the farmstead
Photograph by author

Figure 7.5: Dovetail joinery with chinking
Photograph by author

Figure 7.6: Fieldstone foundation
Photograph by author

Figure 7.7: Cedar shake shingles
Photograph by author

Recording Methodology

For the case of The Log Farm, a combination approach has been taken in regards to the collection of information on site. Both terrestrial photogrammetry and laser scanning were used in conjuncture to develop the final deliverables: point clouds showing the context of the Log Farm

and a separate point cloud focusing solely on the Bradley House. This point cloud has been used as a baseline for the development of a BIM of the Bradley House that can potentially be used to support the CDMICA initiative of vernacular architecture in the Ottawa area. The final recording methodology can be summarized as follows:

Figure 7.8: Recording methodology

Photogrammetry Recording Methodology

The methodology used to record The Log Farm site consisted of a combination of approaches from both Santana’s CIVE 5705 Tutorial 1 Lecture, as well as two lectures given by Nocerino at the 2016 CIPA Summer School in Valencia, Spain.³²⁹ The workflow of the

³²⁹ Erica Nocerino, “Basic Rules for Photogrammetric Acquisition” (Valencia, Spain, September 30, 2016); Mario Santana, “CIVE 5705- Tutorial 1: Using Photogrammetry for 3D Modeling” (Carleton University, Ottawa, Fall 2016).

photogrammetric recording process consisted of three stages: Pre-Planning Phase, On-site Surveying, and Data Processing.

Planning Phase

Checking Equipment

Before going on site, it was essential to ensure that all of the equipment was in working order for October 3, 2016- the chosen surveying day. Coordination with Stephen Vickers, the Architectural Conservation and Sustainability Lab Technician, was required. This was in order to ensure that the surveying equipment (i.e. total station and tripod) was available for use. The following apparatus were used for the surveying process:

- Leica TS-06 Total Station
- Tripod
- Printed Agisoft PhotoScan Targets
- Scale Bars
- Nikon D3300 DSLR Camera

An additional check was done once the equipment was signed out, by ensuring that the batteries were charged for both the camera and total station. This step seems trivial, but is one that is commonly forgotten. During on-site surveying, time management is an essential skill, and if batteries are not charged, it provides a hindrance to data collection.

Total Station Survey Planning

The total station survey was planned well in advance of the actual survey day because it was important to gain an understanding of the site. By knowing where to position the total station ahead of time, it minimized the number of total station setups required to survey all of the control points. This therefore decreased the amount of time surveying, which meant that more attention

could be paid to the proper acquisition of photographs for the photogrammetric model. This concept again leads back to the principle of managing your time while on site in order to complete all of the survey objectives. Google Maps was used to provide the aerial imagery as opposed to QGIS, which was used for the site maps. This was because the image quality of the aerial images from the Carleton GIS website were unsatisfactory for a 5m scale, and that the Google Maps image presented a clearer image of the Bradley House and its terrain.

Figure 7.9: Map of total station positions
Adapted from Google Maps³³⁰

³³⁰ Google Maps, “670 Cedarview Road, K2R 1E5,” accessed July 2, 2017, <https://www.google.ca/maps/place/670+Cedarview+Rd,+Nepean,+ON+K2R+1E5/@45.2991947,->

Another manner of survey planning was through printing off special coded targets from Agisoft PhotoScan, an example of which is shown below. The purpose of using these targets instead of the more traditional checkerboards was to experiment how well the PhotoScan software could perform automatic target identification. The normal procedure is to go through each of the photos individually and specifically choose the marker location to match what was initially surveyed with the total station. Therefore, this methodology would hopefully cut down on the amount of processing time; an important step with sites containing a large number of control points.

Figure 7.10: PhotoScan coded target
From Agisoft PhotoScan³³¹

Photography Planning

Because photography is the essential process behind photogrammetry, it was important to do due diligence by creating a plan for capturing images of the Bradley House. The first step was

75.7972182,40m/data=!3m1!1e3!4m5!3m4!1s0x4ccdfdc1592763a3:0xa8bab71da0f49b42!8m2!3d45.2964053!4d-75.7917807.

³³¹ “Agisoft PhotoScan,” accessed July 21, 2017, <http://www.agisoft.com/>.

filling out a camera datasheet form for record keeping purposes, a best practice technique that should be incorporated when doing any type of documentation work. This is an important- yet often overlooked step- because it ensures that everything is written down before the preparation of any final documents. An adapted version of that form is shown below:

Table 7.1: Digital Camera datasheet

Adapted from Nocerino³³²

1. Camera Body		
Camera Brand		Nikon
Camera Model		D3300
Sensor Type		APS-C
Sensor Size (mm)	Width	23.5mm
	Height	15.6mm
Image Resolution (Pixels)	Width	6000
	Height	4000
Pixel Size (mm)	$px_{size} = \frac{sensor\ height}{image\ height}$	0.0039
2. Lens		
Lens Brand		Nikon
Lens Name		AF-S Nikkor 18-55mm
Nominal Focal Length (mm)		18-55mm
Maximum Aperture		f/3.5
Minimum Aperture		f/22

Completing Ground Sample Distance (GSD) and Photograph Overlap calculations was the next step. This was done so in order to establish the distance to take photographs at to ensure the appropriate level of detail in the photogrammetric model. The desired scale was 1:50. This meant that the maximum GSD value is 3mm according to Andrews et al.³³³ Therefore, this value was set as the GSD for the following calculations. Calculations pertaining to overlap distance were also done to ensure that the CIPA 3x3 Rules of Photogrammetry were followed by having at least 80% overlap.

³³² Erica Nocerino, “Basic Rules for Photogrammetric Acquisition” (Valencia, Spain, August 30, 2016).

³³³ Andrews, Bedford, and Bryan, *Metric Survey Specifications for Cultural Heritage*, sec. 4.4.2.

$$\frac{px}{GSD} = \frac{f}{D} \text{ (Equation 7.1)}$$

$$D = \frac{f}{\frac{px}{GSD}} \text{ (Equation 7.2)}$$

$$D = \frac{24mm}{\frac{0.0039mm}{3mm}} = 18.5m$$

Therefore, the photographs should be taken at a distance of 18.5m or closer to achieve a GSD of at least 3mm.

$$b = 1 - \left(\frac{\text{Overlap}\%}{100} \right) \times W \text{ (Equation 7.3)}$$

$$W = \left(\frac{D}{f} \right) \times w \text{ (Equation 7.4)}$$

$$W = \left(\frac{18500mm}{24mm} \right) \times 23.5mm = 18100mm$$

$$b = 1 - \left(\frac{80}{100} \right) \times 18100mm = 3600mm = 3.6m$$

A distance of 3.6m between respective photographs should be respected in order to get 80% overlap. Closer distance photographs therefore ensure a higher overlap percentage.

On-Site Surveying

Total Station Surveying

After doing all of the requisite pre-survey checks, the survey was conducted. It took place on October 3, 2016. I had the assistance of Mimi Gagne, a graduate of the conservation architecture program at Carleton University. The total station was first positioned in the Station Setup 1 as shown in Figure 7.9 and natural control points were surveyed on the barn. The purpose of establishing these natural control points first was because if I needed to go back to the site at an additional date to take more measurements, these points would still be there for me to resect to and therefore still be able to work in the same local coordinate system of the site.

Figure 7.11: Control points on barn
Orthophoto created by author

After these were taken, the PhotoScan coded target control points were surveyed around the building, starting with the north façade and moving clockwise. In total, 17 targets (numbered 45 to 62 on Figures 7.12 to 7.15) were used, and each target was identifiable in at least 9 photographs of the total 39 that were used.

A number of other natural points (documented by the 500 series numbers in Figure 7.12) were also taken in order to be used as check points in the event that the control points did not work out. This did not end up being the case, as PhotoScan was able to identify all of the control points automatically.

Figure 7.12: North elevation target locations
 Drawn by Mimi Gagne, used with permission

Figure 7.13: East elevation target locations
 Drawn by Mimi Gagne, used with permission

Figure 7.14: South elevation target locations
 Drawn by Mimi Gagne, used with permission

Figure 7.15: West elevation target locations
 Drawn by Mimi Gagne, used with permission

Photography

After completing the survey of the targets, the next step was photography. Photographs were taken in accordance with the CIPA 3x3 Rules at approximately 8 meters away from the house. Photographs were taken in a circular pattern starting at the north elevation and moving clockwise.

The table below illustrates all of the providence information about the photography procedure:

Table 7.2: Bradley House photography information

Bradley House Photography Information	
Camera Used	Nikon D3300
Focal Length	24mm
Aperture	f/10
Shutter Speed	1/80
ISO	100
Sky Conditions	Overcast
Focus	Automatic
Image Format	.NEF and .JPG

Figure 7.16: Photograph of author taking photographs
Photo credit- Mimi Gagne, used with permission

Data Processing

The photographs were processed using Agisoft PhotoScan. In total, 39 photographs were used for the creation of the photogrammetric models. The typical PhotoScan processing pipeline and explanations of the steps are shown in Chapter 4. A discussion of how the steps were adapted for this particular case study will be included in this section.

There were a number of different photogrammetric strategies attempted during this case study- particularly the use of PhotoScan targets and the creation of an ultra-high quality dense cloud model.

Because special PhotoScan coded targets were used in the survey, the built in function of “Detect Markers” was used to identify the control points. The software found each of the targets that had used, and placed the marking point very close to the center of each of them. Fine-tuning adjustments had to be made for some of the targets, but overall this cut down quite a bit of processing time instead of identifying each marker in each photograph individually. After running the initial camera alignment, the resulting error was 3.7mm. This means that the points surveyed with the total station were on average 3.7mm off from what the model interpreted. At a 1:50 plotting scale, this error is perfectly acceptable, as section 2.2.1 of Metric Survey Specifications for Cultural Heritage notes that the maximum error between survey control points and the final results can be a maximum of 5mm.³³⁴

For the dense cloud results, four different quality models were produced: low, medium, high, and ultra-high. This was done in order to understand the difference in processing time and final model point density for further modelling.

³³⁴ Andrews, Bedford, and Bryan, *Metric Survey Specifications for Cultural Heritage*.

Table 7.3: Dense Cloud Comparisons

Model Quality Comparisons				
Category	Low Quality Dense Cloud	Medium Quality Dense Cloud	High Quality Dense Cloud	Ultra-High Quality Dense Cloud
Number of Points	1,145,956	4,514,649	17,409,841	65,024,944
Dense Maps Generation Time	15 mins, 9 sec	43 mins, 28 sec	5 hours, 1 min	20 hours, 59 minutes
Dense Cloud Generation Time	1 min, 12 sec	1 min, 55 sec	7 mins, 11 sec	40 minutes, 33 sec
*All models were processed using moderate depth filtering settings using 39 photographs. **Ultra High Model processed on CIMS Lab Computer				

From the processing time comparisons and the images of the various dense point clouds, it is shown that the high and ultra-high quality model does produce results with a higher point density than the low and medium level models. These model also took more than five and twenty times as long to process than the medium quality model. Therefore, depending on the level of detail of the final product, a high quality model is usually sufficient. In this case, because time constraints were not a factor, the ultra-high model was generated.

Figure 7.17: Comparison of dense cloud resolution

Top left is the low resolution dense cloud, top right is medium, bottom left is high and bottom right is ultra-high quality. Screenshots by author

Figure 7.18: North-East corner comparison of high (left) vs ultra-high (right) quality dense clouds
Screenshots by author

Point Density Validation

Using the methodology established in the photogrammetry section of Chapter 4, point densities were calculated for the various generated point clouds. CloudCompare software can be used to determine the point density, whereby the point clouds from all of the different quality models are all imported and the same rectangular section is arbitrarily clipped from all of them. This should be done in a relatively flat area of the model to ensure that the plane is not heavily angled. CloudCompare gives the number of points in each segment as well. A 2D Polygon (facet) is fitted to this section, of which the software defines its area. This gives the two parameters needed for calculating the point density of each respective quality model.

Figure 7.19: CloudCompare screenshot of 2D Polygon fitted to rectangular section
Screenshot of model by author

Figure 7.20: Number of points in 2D polygon (illustrated by red outline)
Screenshot of model by author

Figure 7.21: Surface area to be used in point density calculations (illustrated by red outline)
Screenshot of model by author

The table below illustrates the compared point densities for each of the different quality models.

Table 7.4: Point Density Analysis

Point Density Analysis					
	Number of Points in Segment	Area of 2D Polygon (m ²)	Number of Points in 1m ²	Point Density (m)	Point Density (mm)
Ultra-High Quality Dense Cloud	1218244	3.56	342203	0.00171	1.71
High Quality Dense Cloud	286010	3.56	80340	0.00354	3.54
Medium Quality Dense Cloud	68427	3.56	19221	0.00726	7.26
Low Quality Dense Cloud	17501	3.56	4916	0.0145	14.5
5mm Point Density	-	-	40401	0.005	5

Therefore, it can be stated that as long as the segment of the dense cloud has more than 40,401 points/m² then the point density will be lower than the literature value of 5mm and is acceptable for use in further modelling. The best choice to use is the high quality dense cloud model because it is under 5mm and did not take as much time to process as the ultra-high quality did. If time constraints are a factor, the medium quality model could be used because of how close to 5mm the result is.

Laser Scanning

The laser scanning procedure was an experimentation process in regards to both the scanning itself and the post processing workflow for the eventual BIM. As this was the first site that I had scanned myself without the aid of Santana, the data capturing process in particular provided a useful learning experience. The scans themselves focused particularly on the interior and exterior of the barn and Bradley House. I only had full access to those two as some of the sheds and other buildings on site were not structurally sound. Exterior parts of these smaller structures were captured during the scanning process because of the 360 degree view of the scanner.

Planning Phase— Justification of Laser Scanning Use

The first example of pre-planning was to examine the reasons as to why laser scanning would be the best recording technique to capture information of the barn and Bradley House at The Log Farm. This was important because if the technique cannot be justified, then there would be no purpose of using it, and other techniques could have been used instead.

From past experiences running tutorials for *CIVE 3207- Historic Site Recording* at the site, there were many difficulties in regards to setting up the total station inside the house and barn for

to take measurements. This was because of the uneven floors and tightly confined spaces. Hand measuring could have been used to document the site, but it would have been a much more time consuming task and was not the aim of my research.

Photogrammetry was deemed a possibility for the creation of a point cloud, but a large number of photographs that would be required to construct the final model. As well, the tightly confined spaces would result in photographs with too steep of an angle due to lens limitations. A wide-angle lens could be used to solve this problem, but it would again be too time consuming of a task to photograph all of the walls, and details in the barn and house. It would also be difficult to document the root cellar and interior barn spaces using photogrammetry because of the lack of lighting. External lighting sources like flashes could be used to solve this problem, but would result in a higher time cost of doing the work.

As the project goal was to establish a basic geometry of the house for modelling purposes, it was decided upon that laser scanning would be the best tool for the job because of the amount of data it can collect in a small time period and the relative ease of registering the data to the existing survey coordinates. As well, cost factor was not taken into consideration due to the fact that I would have access to the Faro Focus X330 laser scanner through Carleton Immersive Media Studio to complete the work.

On Site Surveying

Total Station Survey

Before starting scanning, it was important to establish more control points that could be used to help register the scan data. Therefore, a series of paper targets were placed at strategic locations around the site that were surveyed with the total station. A resection was done in order to link into the project's existing local coordinate system by surveying the natural control points

on the barn shown in Figure 7.11. Thirteen new control points were taken around the site before scanning commenced.

Figure 7.22: UAV Photograph of laser scanning set up
Photograph by author

Scanning Methodology

Figure 7.23: Author scanning on site
Photograph by Sujan Shrestha, used with permission

On the first day of scanning, November 24, 2016, scans were taken of the encompassing barn area and the exterior of the house. My procedure was to go around the barn in a counter-clockwise manner to capture the exterior facades while ensuring there was sufficient overlap between the scans for registration purposes. After this, scans were taken of areas leading into the barn itself as a way of tying the eventual interior area scans with the exterior to create a complete point cloud.

As there was not enough time to finish scanning on November 24, another round of scans was conducted on November 30, 2016. During this visit, scans were done of the interior of the barn and the mezzanine level, and the entirety of the Bradley House.

The most difficult part of that day's scanning activities was the scans tying the mezzanine level of the barn with the exterior of the barn. This was because the way up to the mezzanine in the barn was through a trapdoor that did not provide enough of an overlap if the scanner was placed above and below the opening. Therefore, an alternative approach was implemented whereby the door at mezzanine level was opened to allow for a viewpoint from the upper level to the exterior. Spherical targets placed at the opening of the mezzanine level as well as on the ground, where they could be seen from both scanning locations in order to properly register the scans in Faro SCENE. This approach is shown in the two planar view images of the scans below:

Figure 7.24: Planar view of scan looking up to mezzanine level showing Faro spheres
Screenshot of model created by author in Faro SCENE

Figure 7.25: Planar view of scan from mezzanine level showing spheres
Screenshot of model created by author in Faro SCENE

For the Bradley House, scans were taken of the exterior, interior, and root cellar spaces. Spheres were again used for helping to tie the scans from the root cellar to the building exterior, and for combining the exterior facades with the interior spaces. These spheres were placed in strategic locations that could be seen from 2 or more scanning positions in order to help register the scans based upon these common objects.

After reviewing the scans taken during the second day on site, there were a number of additional problems that had to be solved with a third scanning visit, taking place on December 7, 2016. The interior-exterior spaces in the barn, house, and root cellar were not registering due to lack of overlap, and that the error of the mezzanine level sphere registration was too high. The first issue was resolved through taking what are called “pinch-point” scans. These are scans that are taken in the middle of doorways or openings to allow for enough overlap to align interior and exterior scans (or room to room scans when dealing with interior spaces). Therefore, three scans

are needed to merge interior and exterior spaces (interior scan, pinch point scan, exterior scan). The relative error of the mezzanine scans was solved by re-doing the scans from the ground and mezzanine level by placing the spheres closer together so they could be identified in the scans more clearly. Table 7.5 provides a summary of what areas were scanned on each scanning day.

Table 7.5: Laser Scanning Summary

Scanning Day	Scan Names	Overview of Captured Information
November 24, 2016	Logfarm_Project_Scan_000 to Logfarm_Project_Scan_024	Barn Exterior and Interior; Exterior of Bradley House
November 30, 2016	Logfarm_Project_Scan_025 to Logfarm_Project_Scan_053	Barn Mezzanine Level; Barn Hay-Storage Area; Bradley House Exterior, Interior, and Root Cellar
December 7, 2016	Dec7_Scan_000 to Dec7_Scan_021	Barn Hay Storage Area; Bradley House Root Cellar; Bradley House Exterior; Barn Mezzanine

As the BIM for this site was to be at a 1:50 scale, it was important to establish the point density of the scans in order to abide by the Historic England Standards. Section 7.2.4 states that the point density at a 1:50 scale is 5mm.³³⁵ Therefore, this value guided the scan parameters for the work. A table showing the scan parameters for the general groups of scans is shown in Table 7.6. These parameters indicate the point distance when the scanner is 10m away from the object of interest. When the scanner is close than 10m, which was the case in almost all of the scans, then the point distance will be less than what is indicated.

³³⁵ Ibid.

Table 7.6: Log Farm scanning parameters

	Scan Type	Scan Quality	Scan Resolution	Scan Duration	Point Distance (mm/10m)
Central Site Scans	Outdoor 20m...	4x	1/4	11 min 22 sec	6.136
Barn Exterior	Outdoor...20m	3x	1/4	7 min 47 sec	6.136
Barn Interior	Interior...10m	3x	1/4	7 min 47 sec	6.136
Bradley House Exterior	Outdoor 20m...	4x	1/4	11 min 22 sec	6.136
Bradley House Interior	Indoor...10m	3x	1/4 1/5	7 min, 47 sec 6 min, 30 sec	6.136 7.670
Bradley House Root Cellar	Indoor...10m	3x	1/4	7 min, 47 sec	6.136

Scanning Limitations, and Site Constraints

It is important to note that using the laser scanner does not guarantee perfect results when recording historic sites. The biggest obstacle are occlusions in the scans. If the scanner does not have a direct line of site to objects of interest, then they will not be included in the point cloud because the laser cannot reach them to be measured. This occurred in many scan locations in the barn due to the multitude of structural elements, as well as inside the Bradley House due to all the furniture and structural elements. Because I was looking predominately for geometry of elements versus the creation of a model highlighting precise details, this was not of great concern during the scanning on site.

Another challenge was scanning the attic level of the Bradley House in order to capture the roof structure. There was a trapdoor leading up to the attic level, but due to safety constraints of having to climb up a 10-foot step ladder to scan the attic, this was not feasible. Therefore, the roof structural elements were not scanned and will be approximated in the final BIM.

Ensuring that the paper target control points stayed attached to the buildings was a more serious difficulty faced. This was one instance of poor planning, as the tape used did not stick to the wooden building members. This resulted in a number of targets falling off after they had been surveyed with the total station, which meant that they were not captured in the scans. An approach that can be done to ensure that this does not happen again is to both buy stronger tape, and put up more targets as a contingency plan.

Finally, there was no external power on site, which meant that all of the equipment had to be charged before coming on site. This did not end up being a problem, as the two scanner batteries had more than enough power to last the work day.

Data Processing

The raw scan data was processed using Faro SCENE software.³³⁶ SCENE is based on a cluster style registration, whereby scans that are of similar areas can be clustered together and then locked in place. These clusters can then be merged together to generate the final model. In one sense, scan registration can be seen as fitting the pieces together in a puzzle to create the full representation of the surveyed area.

SCENE includes three types of registration procedures to align the collected scan data: Top View, Cloud to Cloud, and Target based. Each has their own benefits to creating a final model with a high accuracy, with a resulting low registration error. The software also has a number of different ways to view the scans themselves. Correspondence View indicates the scan position in 3D space. There is also planar view, which showcases a flat image of the scanned area. Finally, there is 3D View which can also be used to see the raw scans and point clouds in 3D space.

³³⁶ FARO Technologies Inc., “FARO Laser Scanner Software - SCENE - Overview.”

Top View Registration is based off of manually moving the individual scans to align with one another both from the top and side when in correspondence view as shown by Figure 7.26. When first entering the correspondence view, all of the scans were rotated and translated out of their correct orientation. Therefore, I had to manually move the scans for this method. Once the scans are closely aligned from the top, the side view was checked.

Figure 7.26: Before and after views of manual scan placement

Left side is top view, while the right side images illustrate the side view. Screenshots of model created by author in Faro SCENE

When registering the scans, good practice is to keep the subsampling and reliability settings at approximately $\frac{3}{4}$ for the first iteration, and then move them to the lower subsampling setting to get more refined results. Running the registration at least 2 times was necessary in order to produce a final model with a low registration error, which was defined through experimentation with the software.

Cloud to Cloud registration was used when there was a large amount of overlap sufficient overlap between respective scans. The software then automatically aligns them without manual input required. As was done with Top View, the subsampling setting was kept to about $\frac{3}{4}$ during the first iteration, and then moved lower until the results are acceptable for the project. That meant a registration error of less than 5mm.

Figure 7.28: Recommended registration settings for top view registration
Screenshot by author

Figure 7.27: Recommended registration settings for cloud to cloud registration
Screenshot by author

The final way to register the scans was through target based registration, commonly referred to as manual registration because of the amount of software interaction required as compared to top view and cloud to cloud. Targets were placed in scans in order to help with the registration. The purpose of the targets is that they are detected by the software and can be used as tie points between the scans to place them in their correct positions. The targets must be kept in the same location in the various scans, or else the alignment process will not work based on that method. These may be checkerboards or special spheres. Checkerboards are common surveying

targets, whereas spheres are special Faro targets used to help align scans. At least 3 of the same spheres or checkerboards should be seen in two or more scans for this method to work. I manually selected these objects in the scans and ensured that they had the same name in each scan to help with the alignment.

Each of the three methodologies was best used based on the specific scenario. Target based was best when entering smaller spaces or adjoining rooms, or with different floors in a building such as the mezzanine for the barn. This enables the software to join scans on different elevations or around tight hallways quite easily and with very little overlap, a feat that would not be possible for top view or cloud to cloud. From experience with the software for this research, a good approach was to first use top view to approximate the positions of the scans, and then use cloud to cloud to improve that alignment based off of the overlap. Additionally, as stated earlier, it was always best to start with high subsampling, and then refining it to a lower setting during the second, third, or fourth iterations.

Faro Scene Log Farm Processing Approach

When registering the data in Faro SCENE, two separate point clouds were created— one showcasing the farm in its context to gain an understanding of the farm experience, and the second focusing on the Bradley House for the development of a BIM. Therefore, the model quality in regards to the post-processing would be less for the barn and outbuildings and more for the Bradley House, as it would be important to get a concise point cloud for BIM purposes.

The approach that was taken for the entire site was creating two clusters: one for the barn, and the other for the Bradley House. The scans in each main cluster were composed of a series of smaller clusters based off of the scan locations. For example, for the barn, it was broken down into clusters such as “Barn Front”, and “Barn Rear.” Each cluster was aligned with a combination of

the three registration techniques. In order to combine both of these final clusters, target based registration was used by setting the control points to global origin, and registering the clusters to the control points that were measured with the total station. Checkerboard targets were chosen on scans in both the barn and house cluster, and then all brought into the same coordinate system by using the references to align them. The benefit of doing this is that the final model is in the same coordinate system as the photogrammetric model of the house. This was done through setting the references as global origin.

Because the house was the object of interest, the house cluster was then exported into a new project file for further refining and cleaning before the point cloud was exported. The site model as a whole was left uncleaned (i.e. keeping trees, vegetation, and fences) to show the Bradley House and barn in its surrounding landscape.

The scans were cleaned using both 3D View and Planar View. For example, Figure 7.29 below shows a 3D view of points outside the room of interest. Therefore, those points were deleted because they did not contribute to the final point cloud.

Figure 7.29: Cleaning scans in 3D View in Faro SCENE
Screenshot of model by author

Figures 7.30 and 7.31 show how planar view was used for cleaning more precise areas. By selecting specific elements of interest in planar view, they can be viewed in 3D view for a more accurate way of deleting unwanted points. This methodology was particularly useful in scans containing windows, as the glass does not refract the laser, and creates unwanted information outside of the rooms of the house. A final way that the scans were cleaned was through the filter tool. It was able to filter stray points based by distance, point intensity, and overlap to help clean the final model.

Figure 7.30: Selecting areas to clean using planar view in Faro SCENE
Screenshot of model created by author

Figure 7.31: Resulting 3D view of area selected in planar view
Screenshot of model created by author

After cleaning had been accomplished, the scans were exported into a ReCap format to be used as a base model to trace from in Revit for the BIM. As the ultra-high quality point cloud of the exterior of the house from photogrammetry was of much higher density (thereby being able to see the dovetail joinery details) and contained better colour than the point cloud taken from the laser scanner, the photogrammetric point cloud was used instead to represent the exterior of the house. Therefore, this was accomplished by combining the point clouds in Autodesk ReCap because they were all based off of the same local reference.

Once the scans were all imported, errors were noticeable. There was an approximately 5cm difference between the photogrammetric model point cloud and that of the laser scans. This problem was solved by importing the GCP surveyed during the photogrammetric survey into the SCENE file of the Bradley House. Individual scan points were selected in SCENE close to the locations of where the PhotoScan targets were located. Target based registration was to align the model to the new control points. This again gave a high error, so a second strategy was tried in order to manipulate the laser scan model to fit into the GCP target locations. The coordinates of the chosen scan points were changed to match those of the survey points. The next time target based registration was run, the error was of sub millimetre accuracy. In order to validate these results, the entire point cloud model was exported back into ReCap and compared with the ultra-high photogrammetric model. The two sets of point clouds now aligned in their correct locations, and there was no noticeable error between two sets. After these results were validated, the façade areas of the laser scan point cloud were clipped to only showcase the terrain around the house. This was because they would no longer be useful because of the higher density point cloud to showcase the exterior façade.

Log Farm Registration Statistics

Below are the final registration statistics of the registered scans. The comparison is based off of the regular scan results, which showcases the average error between the scans that were used to register the clusters together versus the whole hierarchy, which includes all of the scans that were registered together.

Table 7.7: Log Farm registration statistics

Log Farm Scene Registration Statistics		
	Mean Error	<4mm
Whole Farm Site	6.62mm	35.9%
Whole Farm- Full Hierarchy	4.03mm	54.8%
Bradley House	6.64mm	33.4%
Bradley House- Full Hierarchy	2.60mm	67.2%

According to Section 7.2.4 of *Metric Survey Specifications for Cultural Heritage*, at a 1:50 scale, the point density and precision is to be 5mm.³³⁷ The final error is above that value for the non-hierarchy results. A reason as to why it is higher is because of all of the exterior scan alignments, and aligning over longer distances without sufficient overlap. Interior scans of the spaces aligned with a much lower error and a higher overlap percentage. Therefore, the way that these results can be interpreted is that either a higher quality scan is necessary to get a higher point density, or the fact that more connecting scans between the exterior areas connecting the barn to the Bradley House should have been conducted in order to get that higher overlap. Additionally, another interpretation is that more control points should have been surveyed when scanning as to utilize the target based method of registration, which is highly accurate due to the smaller relative errors of the total station survey.

³³⁷ Andrews, Bedford, and Bryan, *Metric Survey Specifications for Cultural Heritage*.

Deliverable: BIM of the Bradley House

As the generated point cloud data is just a series of points, it must be interpreted. Therefore, one way that this is accomplished is through the use of a Building Information Model, whereby the point cloud serves as a base upon which building elements can be created for the formation of a complete drawing set and management tool.

In regards to the creation of a BIM, Autodesk Revit software was used. The point cloud was imported into Revit and locked into place, so it would not move during the model generation. The procedure followed when modelling in Revit came from the protocols established by the CIMS Lab. Features such as element verification were very important, because in some areas, there were occlusions due to obstructions when scanning. Therefore, these areas were carefully noted in the Revit model as being an assumption of the geometry of the objects, and that it was not verified with the point cloud.

As the geometry of the point cloud proved to be difficult to model in Revit, a number of assumptions were made. The first was that the log walls would be modeled as straight elements due to the level of difficulty of generating specific wall contours and drawing each individual log. Another assumption was that the warped beams and columns in the root cellar would be modeled as straight due my skill set and overall lack of time. The warped floors also proved to be problematic, and were designed as straight elements.

The walls themselves were aligned to the proper thickness and general outline of the point cloud, which provided a basic representation of how they have deformed over the years instead of being in a perfect rectangular configuration. Window and door elements were simplified in the model because they were not original and therefore did not require a high level of detail. This

meant that the standard Revit loadable families for windows and doors were used instead of designing a new geometrically accurate element to represent these details.

Each of the individual elements was modelled in separate Revit families to make use of the parameters function of the materials depending on the geometry of the object. In regards to the timber aspect of the model, because Revit does not have a built in timber framing system, walls were modelled as simple elements instead of individual logs with mortar joints, and beams and columns were specifically made to fit the sizes shown in the point cloud.

The rationale behind these modelling decisions stems from the fact that the goal of the model was to generate a basic geometry of the house at a 200-300 LOD. It is a basic simplification of the existing structure. Users with a Revit skill set greater than my own (i.e. those that have taken Revit courses/modules) can add to the model to make it more realistic. Screenshots of the final model and element geometries are shown below:

Figure 7.32: North-South section cut of model and point cloud (looking north)

Figure 7.33: North-South section cut of model (looking south). View also shows singular wall elements

Figure 7.34: Plan view of root cellar showing the difference between BIM elements versus what was captured by the point cloud
Image also shows warped members, which were not modelled in Revit due to the complex geometry

Not Enough Point cloud information

Figure 7.35: Plan view of root cellar showing revision bubble indicating area with no point cloud information

Figure 7.36: Another view showing the discrepancy between the point cloud and what was modelled in BIM

Figure 7.37: Screen capture of wall families created in Revit

Chapter Summary

This chapter described the workflow of using photogrammetry and laser scanning in conjuncture to document the Log Farm. The reason as to why both of these techniques were used was because of the limitations of each technique individually. Photogrammetry was best used to document the exterior of the Bradley house, while laser scanning was best suited for the interior work. Together, a final point cloud model was produced that was used for the BIM of the Bradley House. The BIM was developed to show the basic geometry of the house to be used for posterity record keeping.

Chapter 8: Prince of Wales Fort

Introduction

Prince of Wales Fort is located in Churchill, Manitoba, at the mouth of the Churchill River (Figure 8.1). The main interest in the Prince of Wales Fort site revolved around the chosen documentation technique: UAV photogrammetry. This site presented a unique opportunity to examine how the technique is used in practice and the resulting photogrammetric models that can be generated from aerial photographs taken from commercially available UAVs. The project goals for the Fort relate to research gaps 1 and 2: further analysis of collected information, and how UAVs can be used for documentation purposes. Figure 8.2 displays the wall naming conventions used by Heritage Conservation Services, of which the wall naming conventions will be referenced over the course of this chapter.

Figure 8.1: Google Maps image of Prince of Wales Fort Location
From Google Maps³³⁸

³³⁸ Google Maps, “Prince of Wales Fort,” accessed February 13, 2017, <https://www.google.ca/maps/place/Prince+of+Wales+Fort+National+Historic+Site/@58.7642573,->

Figure 8.2: Wall naming conventions of Prince of Wales Fort by the Heritage Conservation Services
Image created by author

Site History

The site itself was constructed over a 40-year period from 1731-1771 by the Hudson's Bay Company in order to protect their northern trade routes.³³⁹ It was constructed from quartz wacke and built in two phases.³⁴⁰ The masonry type used in each of the phases is different, hence the

94.1491927,12.22z/data=!4m5!3m4!1s0x526fd936220be4fd:0xb50ac3f136caa09b!8m2!3d58.797175!4d-94.213122.

³³⁹ Jacqueline Hucker and Canadian National Historic Sites Directorate, "Prince of Wales Fort: A History, Documentation and Analysis of the 20th Century Repairs to the Outer Walls," 1994.

³⁴⁰ Lyne Fontaine and Cam Elliot, "Impact of Climate Change on Prince of Wales Fort: The Conservation Process and the Adaptation Strategy" (Heritage Conservation Directorate-Public Works Government Services Canada, 2007).

marked difference in appearance of various wall sections of the fort. The first phase (1731-1740) was constructed of split boulders and clay mortar.³⁴¹ Figure 8.3 is of the north-east bastion, which displays the split boulder design.

Figure 8.3: North-east bastion (Wall Sections JK, KL) - split boulder construction
Photograph by author

The second phase of construction, taking place from 1740 until 1771, was necessary because of the initial performance issues with the split boulder walls. The rampart was not wide enough for recoil of cannon fire, and a stone parapet was required to enhance defences against French forces.³⁴² Therefore, a new rampart had to be reconstructed, for which they used ashlar stones with lime mortar.³⁴³ Because the lime mortar never had time to cure due to frost conditions, the overall condition of the ashlar walls today is worse than the split boulder.³⁴⁴ This is evident

³⁴¹ Ibid.

³⁴² Ibid.

³⁴³ Ibid.

³⁴⁴ Ibid.

through visual inspection of images taken on site, as bracing is used in specific sections of the fort to help stabilize it, such as in wall section EF, FG, in the north-west bastion (Figure 8.3):

Figure 8.4: North-west bastion with bracing
Photograph by author

The French damaged the fort in 1782, which caused the Hudson's Bay Company to cease operations.³⁴⁵ It was left dormant and neglected for 150 years until conservation initiatives were the Historic Sites and Monuments Board of Canada put forth conservation initiatives.³⁴⁶ The conservation efforts of the 1930s and 50s focused on the stabilization of the exterior rampart walls,

³⁴⁵ Parks Canada, "Prince of Wales Fort National Historic Site of Canada," accessed June 14, 2017, <http://www.historicplaces.ca/en/rep-reg/place-lieu.aspx?id=7760&pid=0>.

³⁴⁶ Hucker and Canadian National Historic Sites Directorate, "Prince of Wales Fort: A History, Documentation and Analysis of the 20th Century Repairs to the Outer Walls."

as some sections were in danger of collapse.³⁴⁷ As the site was open to the public, safety of the site was a critical priority as to not put any visitors at risk of injury. The initial interventions did indeed help to ensure the continued longevity of the site. The repair techniques used negatively impacted aspects of the site's authenticity. Specifically, cement was poured behind the walls as a consolidation technique, which today is seen as a very intrusive intervention.³⁴⁸ This erased any signs of 18th century craftsmanship in the specific areas that were commissioned for repair.³⁴⁹ The site has also been greatly affected in recent years due to climate change due to rising temperatures. Visible cracks and masonry deterioration are visible on site, and monitoring programs have been put in place in order to keep a detailed record of any changes. A report commissioned in 2007 by Heritage Conservation Services-Public Services and Procurement Canada discussed the impacts of climate change on the fort.³⁵⁰ Some of their main findings were:

- 1) Areas that have been exposed to more sun radiation deteriorate at a quicker pace than areas that do not face direct sunlight.³⁵¹
- 2) The north wall, formerly in a state of permafrost, now thaws for longer time periods. This results in further deterioration to the lime mortar, an already poor choice for transferring the load of the stones above.³⁵²
- 3) Frost jacking causing bulging and cracking of ashlar masonry face stones.³⁵³

³⁴⁷ Ibid.

³⁴⁸ Ibid.

³⁴⁹ Ibid.

³⁵⁰ Fontaine and Elliot, "Impact of Climate Change on Prince of Wales Fort: The Conservation Process and the Adaptation Strategy."

³⁵¹ Ibid.

³⁵² Ibid.

³⁵³ Ibid.

Identified Heritage Values

The site was designated as a National Historic site in 1920, but formally put on the *Canadian Register for Historic Places* in 2007. It was designated because of both architectural and historical significance. In regards to historical values, the site serves as a landmark to the English-French competition for Northern Canada in the 1700s, more specifically, access to Hudson Bay.³⁵⁴ In terms of architectural values, this stems from the materiality and scale of the Fort. The walls are up to 12 meters thick in some areas, which illustrate the defensive sense of power that the structure portrays.³⁵⁵ Some of the character-defining elements of the site include:

- The relationship between the Fort and its surrounding environment, specifically with respect to the flat tundra landscape³⁵⁶ (Figure 8.5)
- The star-shaped footprint of the Fort³⁵⁷ (Figure 8.6)
- The use and materiality of local stone used in the construction of the Fort³⁵⁸
- Evidence showcasing the past functionality of the Fort through the conservation of functions such as the bastions, gate, and ravelin³⁵⁹
- The view of the Churchill shorelines from across the Churchill River³⁶⁰ (Figure 8.7)

³⁵⁴ Parks Canada, “Prince of Wales Fort National Historic Site of Canada.”

³⁵⁵ Ibid.

³⁵⁶ Ibid.

³⁵⁷ Ibid.

³⁵⁸ Ibid.

³⁵⁹ Ibid.

³⁶⁰ Ibid.

Figure 8.5: Prince of Wales Fort with respect to its landscape
Photograph by author— taken by UAV

Figure 8.6: Screenshot of mesh model showing the star-shaped plan of the Fort
Model created by author, screenshot by author

Figure 8.7: View of Prince of Wales Fort with the Churchill shoreline in the background
Photograph by author—taken by UAV

Documentation Methodology

The general overview of the documentation methodology is shown in Figure 8 below. These steps will be further examined in the following sections.

Figure 8.8: Documentation Methodology

A) UAV Research for Cultural Heritage Applications

The first step in the workflow was developing an understanding of how UAVs are used in the field of cultural heritage for image acquisition. Topics such as flight path patterns, camera orientation, the UAV platform used, and data processing workflows were examined during this phase. This accumulation of research done is displayed in the literature review of UAV Photogrammetry in Chapter 4. The decided UAV platform for the project would be the DJI Phantom 4, as Carleton Immersive Media Studio had purchased it for use in the project. The Phantom 4 is a low-cost UAV (as it is under \$2000 CAD) which was a factor in its initial purchase. It has a 1/2.3” sensor, which is smaller than the sensor used for image capture at The Log Farm.³⁶¹ This meant that the distance to the object (i.e. the fort walls) would be a very important factor during image capturing.

B) Special Flight Operations Certificate (SFOC) Application

Based off the literature reviewed, one of the most crucial aspects in preparation for flying UAVs in Canada is determining whether a SFOC is required for the specific project. As the built-up infrastructure located across the Churchill River was less than three nautical miles away (5.5 kilometers), the SFOC exemption did not apply.³⁶² Therefore, a SFOC was required so this project could take place. The site is located within the Prairie and Northern Region of Transport Canada, and as such, the SFOC document had to be prepared to their specifications.

³⁶¹ DJI, “DJI Phantom 4 – Specs, FAQ, Tutorials and Downloads,” accessed July 26, 2017, <https://www.dji.com/phantom-4/info>.

³⁶² Transport Canada Government of Canada, “Exemption from Paragraph 571.08(1)(b) of the Canadian Aviation Regulations,” December 21, 2016, <http://www.tc.gc.ca/civilaviation/regserv/affairs/exemptions/docs/en/2879.htm>.

C) Recording in Churchill (Data Collection)

During the time on site, the wind speeds were approximately 20km/h, and there were only a few instances of rain, which unfortunately shut down the operation for a few hours. In terms of other hardware used, there was one backup battery, and an iPhone 5s, which was being used to control and monitor the UAV through the use of the DJI Go app. There was a generator on site, which was used to charge the UAV batteries and phone battery after each flight.

As we were flying underneath a flight path, this presented another restriction when trying to capture overall site context images at high altitudes. Any time other aerial vehicles were spotted, the UAV was brought back to the operator as an extra safety precaution. The safety mode was turned on, which meant that the maximum altitude of the UAV was 30 m AGL (above ground level). This would help to ensure that the UAV would be within the operator's line of sight at all times.

Figure 8.9: Author flying the Phantom 4 in Churchill
Photograph credit- Melissa Lengies- used with permission

UAV image acquisition

Ten rounds of flights were conducted when on site, all with varying purposes. The flights were done through manual piloting and all images captured were also done manually. The general flight path followed was of the linear nature. The iPhone 5s was used as the hardware for the DJI Go application in order to conduct the flights.

Table 8.1: Flight Test Summaries

Summary of Flight Tests		
Flight Number	Flight Duration	Description of Area Captured with Photos/Video
1	16 min, 14 sec	Nadir images taken at 17-25m height, encircling the perimeter of the fort, specifically the tops of the rampart walls
2	18 min, 29 sec	Nadir photos taken at approximately 12-15m. Photos taken of the west side of the fort
3	18 min, 52 sec	Nadir photos taken at approximately 12-15m. Photos taken of the east side of the fort
4	19 min, 12 sec	Nadir photos taken at approximately 25m of the perimeter of the fort around the rampart walls
5	17 mins, 1 sec	Video overview of the Fort
6	17 min, 25 sec	Oblique Images (20-30 degrees down) at 10-20m height. Captured the east, north, and west walls
7	14 min, 28 sec	Oblique Images (approximately 20 degrees down) of the south wall (entranceway area) and smaller rampart wall at 5-10m high
8	19 min, 41 sec	Oblique images (at 26 and 37 degrees down) of the west side of the interior courtyard area at 6-12m high flight
9	21 min, 45 sec	Oblique images(20-47 degrees down) of the west side of the interior courtyard area, as well as the interior parts of the tops of the rampart walls at 8-13m high flight
10	20 min, 33 sec	Oblique images (head on, 7 degrees down) of specific areas of the fort for test photogrammetry purposes. Images taken at 3m away from wall
11	19 mins, 17 sec	Overview images of the fort at 10.7 degrees down, 40m high, as well as video showing overview
12	18 min, 32 sec	Nadir images of the topography and landscape to integrate with the photographs of the fort. Height of 40m

D) Data Processing

Shown in Figure 8.10 is the methodology used to process the data for the eventual production of two different outcomes: orthophotos to aid in the production of measured drawings

of the site for condition assessment purposes and point clouds to be used for a deformation analysis of the specific areas of the Fort walls.

Figure 8.10: Data Processing workflow

1) Image sorting/file naming/organizing photos

After image capturing, the photos and video footage was sorted based on the date and flight number on that specific date for posterity record keeping purposes. This was done using Adobe Bridge software. Each set of photos corresponded to what was logged in the metadata of each flight, which can be seen on airdata.com. [Airdata.com](http://airdata.com) also displayed the route that the UAV took to capture the images, the altitude that each of the images was taken at, and notifications about the battery life during flight (Figures 8.11 and 8.12). This information can be exported as a .kml file to be used in a Google Maps application for easy sharing of flight data.

Figure 8.11: Example of flight pat pattern for Prince of Wales Fort
Screenshot from airdata.com³⁶³

³⁶³ [Airdata.com](http://airdata.com), “Airdata UAV - Flight Data Analysis for Drones.”

	Flight time	Altitude	Home Distance	Gimbal Pitch	Heading	Type
A	01m 03s	8.2 m	13 m	24.5° down	47°	Photo
B	01m 13s	8.7 m	7 m	24.5° down	45°	Photo
C	01m 18s	8.7 m	5 m	24.5° down	46°	Photo
D	01m 21s	8.6 m	5 m	24.5° down	46°	Photo
E	01m 25s	8.5 m	6 m	24.5° down	46°	Photo
F	01m 31s	8.4 m	7 m	24.5° down	46°	Photo
G	01m 35s	8.4 m	10 m	24.5° down	46°	Photo
H	01m 41s	9.2 m	12 m	24.5° down	46°	Photo
I	01m 45s	9.1 m	14 m	24.5° down	46°	Photo

Figure 8.12: UAV photograph locations at Prince of Wales Fort
Screenshot from airdata.com³⁶⁴

2) PhotoScan

PhotoScan was used to process the collected data. Once again, the standard PhotoScan pipeline was followed (as seen in Chapter 4) but there were more problems processing the data as compared to the Log Farm Site. All of these difficulties, along with how they were solved, is explained in the following pages.

Both nadir and oblique images were captured. Only the oblique images were used in the creation of the photogrammetric model. These resulted from images being used from Flights 6-9.

³⁶⁴ Ibid.

The images were first manually inspected and checked to ensure that they were sharp and would help in the alignment of the photogrammetric model. The image quality was then checked and any that were below 0.75 quality were deleted. This brought the total number of images kept to 767.

Masking the photographs was particularly important during this case study test. This is because of the Phantom 4's very large field of view. The large field of view helped contribute to a large amount of overlap between the images (thereby aiding in the image alignment process) but there was a major drawback. During initial dense cloud testing, images focusing on the exterior walls also included some parts of the inner courtyard, resulting in too much overlap of the images. The dense clouds generated using this initial methodology did not display a high level of detail of the interior courtyard masonry elements. Therefore, by masking all of the interior courtyard details from the exterior ring of photographs, it helped to solve this problem.

The next difficulty encountered was in regards to image alignment. During the first image alignment iteration, a strategy of creating two separate chunks consisting of the exterior walls and interior courtyard was conducted. Control points were not used to help register the model. This resulted in major errors such as not all images being registered and improper alignment of the chunks as they were aligned on top of one another.

The way that this problem was solved was twofold. The first method was by adding control points to each of the images to help register them in place. 161 control points were used to help register the model and provide the proper scale. The second way that this was accomplished was by removing the exif data pertaining to the GPS coordinates of the images. This is because there is an error with that data in some images in regards to the height of the UAV when the image was taken, and because of that, PhotoScan interpreted interior images as being on top of the exterior ones. Four separate alignment iterations were tested to compare their accuracy results in order to

determine which had the highest accuracy (lowest relative error) to continue the processing with.

These chunks were:

- 1) GPS and without GCP, (GCP being added after the initial camera alignment)
- 2) Without GPS and without GCP (GCP being added after the initial camera alignment)
- 3) GPS and with GCP (adding the GCP before alignment to aid in that process)
- 4) Without GPS and with GCP (adding the GCP before alignment to aid in that process)

By doing these four tests, they helped to determine the effect of the exif data (latitude, longitude, altitude) on the generation of the model, as well as determining how big of an impact adding the control points was (i.e. whether we add them at the beginning of the process when we mask, or adding them afterwards). The meaning of the control point error is the distance between the survey coordinates of the total station, and the estimated position of the point marker from PhotoScan.³⁶⁵ Based off of the control point errors in Table 8.2, Chunk D was chosen as the one that would be used going forth. After this was done, cameras were optimized, which resulted in even better accuracy as seen in D- Optimized cameras in Table 8.2.

Table 8.2: PhotoScan control point errors

PhotoScan Control Point Errors	
Chunk Name	Control Point Error
A-Camera Alignment with GPS (GCP added after alignment)	0.020351m
B-Camera Alignment Without GPS (GCP added after alignment)	0.018937m
C-Camera Alignment With GPS (GCP used in alignment)	0.019916m
D-Camera Alignment Without GPS (GCP used in alignment)	0.018937m
D-Optimized Cameras	0.009365m

In order to validate these results, Andrews et al., cites values that are acceptable for these errors for the generation of measured drawings.³⁶⁶ According to Section 4.5.2, the accuracy for a

³⁶⁵ Agisoft LLC, "Agisoft PhotoScan User Manual Professional Edition, Version 1.1," 2014, http://www.agisoft.com/pdf/photoscan-pro_1_1_en.pdf, pg 37.

³⁶⁶ Andrews, Bedford, and Bryan, *Metric Survey Specifications for Cultural Heritage*.

1:50 drawing set is 9mm.³⁶⁷ Therefore, this value is very close to the 9.4mm error obtained by PhotoScan, which for this case, is an acceptable error.

For the dense cloud processing, low, medium, and high quality dense clouds were generated. The amount of time and relative number of points contained in each model is shown in Table 8.3.

Table 8.3: Dense Cloud comparisons

PhotoScan Dense Cloud Comparisons		
Dense Cloud Quality	Number of Points	Processing Time
Low	~13,000,000	Depth Maps- 45 min 46 sec Dense Cloud- 45 min 49 sec
Medium	~51,000,000	Depth Maps- 3 hours 43 min Dense Cloud- 5 hours 1 min
High	~200,000,000	Depth Maps- 23 hours 7 min Dense Cloud-1 Day 5 hours
**All Point Clouds were processed on CIMS computers		

Unfortunately, generating a mesh model from PhotoScan was unsuccessful, as the software kept crashing due to the constraints from the computer hardware. 32GB of RAM was not enough to process the mesh. The importance of generating a mesh is that in order for orthophotos to be generated, a mesh is required for them to generate onto. This step had to be completed to produce the deliverable required to complete the measured drawing. Therefore, an alternative strategy was used, whereby the images were imported into ContextCapture for the mesh generation step.

3) ContextCapture

ContextCapture software was introduced to me by visiting Professor Luigi Barazzetti, who specializes in geomatics and photogrammetry at Politecnico di Milano in Italy. He provided me a methodology such that the aligned photographs from PhotoScan could be imported into ContextCapture without having to mark control points on each of the images again. If the markers would have to be identified again in each image in ContextCapture, it would be a very time

³⁶⁷ Ibid.

consuming step. Luckily this was not the case, as the aligned camera parameters for each image were exported from PhotoScan and then imported into ContextCapture. The methodology for importing photograph alignment information from PhotoScan to ContextCapture is summarized in Appendix B.

The benefit of using ContextCapture for mesh (and dense cloud processing) is that it is RAM dependent. Using the ‘Adaptive tiling’ setting, a specific amount of RAM can be allotted for the generation of meshes or dense cloud models (Target RAM usage in Figure 8.13) by separating the model into a series of individual tiles instead of one whole model like is done in PhotoScan.

Figure 8.13: Adaptive tiling feature in ContextCapture
Screenshot by author

For the case of this model, 16GB was the targeted RAM usage (half of the available RAM on the computer), which resulted in 16 separate tiles being created. The point cloud tiles were also generated from ContextCapture as an automatic step in the creation of a mesh. The resulting mesh and point clouds were automatically cleaned of excess noise points from the sky, which was a benefit that did not occur in PhotoScan. This was also done with no masking involved, as that function does not exist in ContextCapture. The control point errors were not of relative concern in ContextCapture, as they had already been calculated in PhotoScan. Running the model again in ContextCapture would be a possibility to determine the relative error during the photo alignment step. It would involve repeating the marker picking process on all of the photographs, resulting in

a very time consuming process for an additional accuracy of a few millimetres. This was deemed not to be worth the extra time value involved.

4) CloudCompare

As the ContextCapture generated 16 individual mesh files, they had to be first merged with one another, as PhotoScan can only import one mesh per chunk. Therefore, CloudCompare was used to align the meshes and then export them back into PhotoScan to be used for the orthophoto generation.

5) PhotoScan

The new .obj file was then imported back into the PhotoScan chunk, which aligned in the same coordinate system as the dense cloud model because of the fact that the same camera parameters were used in the ContextCapture model generation.

A series of orthophotos were then created for individual wall sections of interest. The importance of adding the mesh back into the PhotoScan file was because of the usability of PhotoScan for orthophoto generation. The orthophotos had an approximate resolution of 5mm per pixel. Though that result is higher than the 3mm value for a 1:50 scale noted by Section 4.7.4 of Andrews et al., from visual inspection of the image, the mortar joints and individual stones were all clearly visible to be traced for an elevation drawing.³⁶⁸

Figure 8.14: Orthophoto of Wall Section O-P
Model created by author, screenshot by author

³⁶⁸ Ibid.

E) Deliverables: Measured Drawings and Analysis

There were two primary deliverables that were generated based off of the recording data. These include measured drawings based off of orthophotos that can be used for condition assessment purposes, and the establishment of a multi-temporal planar displacement analysis for specific sections of the fort that were captured with close-range UAV photogrammetry.

6a) AutoCAD Measured Drawings

From the orthophotos generated from PhotoScan, a measured drawing application has been done in AutoCAD in order to draw out the individual stones to be used for condition assessment purposes the next time work is done at the site. As the exported orthomosaic from PhotoScan was unscaled, the point cloud generated for the site was used to scale the orthoimage in AutoCAD. The reason as to why the drawing was not drawn directly from the point cloud is because the orthoimage was easier to visualize and provided a more detailed view of the stone locations. Appendix C displays an example of a measured drawing for Wall Section O-P. The decided scale was 1:50, as it is a standard size for elevation drawings and all of the stones and mortar joints can be seen.

6b) CloudCompare Deformation Analysis

Due to the effects of climate change, a multi-temporal deformation analysis was deemed as a beneficial deliverable to make the best use of the data collected. The purpose behind this type of structural health monitoring strategy is that information collected from different time periods can be compared based on the same datum. This can be done using the open source software CloudCompare.

The information used for this analysis comes from point clouds generated in PhotoScan by using images from Flight 10, which were photographs taken at an angle perpendicular to the wall

surface. This type of UAV photography methodology was done in four separate locations around the site. The section used for this analysis is that of Wall section E-F (in accordance with the Wall Naming conventions in Figure 8.2). The datum used for this analysis is a best-fit plane, as the wall is rectangular in shape. A screenshot of the plane can be seen below.

Figure 8.15: Screenshot of best-fit plane applied to point cloud in CloudCompare
Model created by author, screenshot by author

This same plane can be used to compare point clouds from future interventions, because all the user has to do is import it into a new CloudCompare project along with that epoch's point cloud. After the plane is imported, a cloud to mesh algorithm is run in order to determine the relative distance between the point cloud and the reference primitive. Shown below is the resulting scalar field and its histogram. One thing to note is that CloudCompare is a unit-less software. Therefore, the values shown are in the same units as what the point cloud was originally developed in, which in this case is meters. The areas in red and orange in Figure 8.16 are indicative of outward bulging of the wall, as that direction was deemed to be the positive axis. Areas in yellow and light green represent a planar surface, while dark green and blue represent areas where the wall turns back in on itself. These types of strategies can be used to develop wall threshold limits in regards

to intervention strategies, i.e. if the wall bulge reaches a certain value, then conservation work is required immediately.

Figure 8.16: Scalar field wall deformation distances (units in meters)
Screenshot of model created by author

Figure 8.17: Histogram of deformation analysis (units in metres)
Screenshot by author

Chapter Summary

This chapter focused on how UAVs were used to document the Prince of Wales Fort site. The workflows focused on ensuring UAV regulations were followed, and the manner in which the information was captured with the UAV through the use of oblique images. The quality of the results produced indicated that they were acceptable for a 1:50 drawing set of the façade surfaces, with the orthophotos produced having a resolution of 5mm. Additional photogrammetric models were created using images from flights at a distance of 3 metres away from the wall surface that were used in a deformation analysis application.

Chapter 9: QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen

Introduction

QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen are located within the Valley of the Queens and Kings respectively. In turn, these valleys are located within the UNESCO World Heritage Site of Ancient Thebes with its Necropolis.³⁶⁹ The site encompasses 7390 hectares and is within the Qina Governorate.³⁷⁰

The work from this documentation initiative was in regards to research gaps 1, 5, and 6. They discuss about further analysis of products created from digital documentation recording processes, the adaptation of software for heritage conservation applications, and the ways in which information can be disseminated to the public and fellow researchers.

To re-iterate, the project was an interdisciplinary effort between Carleton University, the Getty Conservation Institute and the Egyptian Ministry of Antiquities. Again, all images used here may not be reproduced without the permission of the Getty Conservation Institute.

Figure 9.1: Team members outside QV66: Tomb of Nefertari
Photograph used with permission from The Getty Conservation Institute

³⁶⁹ UNESCO World Heritage Centre, “Ancient Thebes with Its Necropolis,” *UNESCO World Heritage Centre*, accessed July 7, 2017, <http://whc.unesco.org/en/list/87/>.

³⁷⁰ Ibid.

Figure 9.2: Team members inside KV62: Tomb of Tutankhamen
Photograph used with permission from The Getty Conservation Institute

Site Histories

The Valleys of the Queens and Kings served as the main burial ground for members of the Egyptian Royalty more than 3000 years ago. These burial sites are situated to the west of ancient Thebes because of the Egyptian belief that the netherworld was located in the same place as the setting sun.³⁷¹

QV66: Tomb of Nefertari

QV66: Tomb of Nefertari, also known as the “house of eternity” was discovered in 1904 by the Italian Egyptologist Ernesto Schiaparelli.³⁷² Nefertari was the Great Royal Wife of Ramses II, who reigned during the 19th Egyptian dynasty.³⁷³ She had a powerful presence in both state and

³⁷¹ John K. McDonald, *House of Eternity: The Tomb of Nefertari* (London: Thames and Hudson, 1996), 20.

³⁷² *Ibid.*, 21.

³⁷³ *Ibid.*, 9.

religious affairs, and was active during the reign of Ramses II.³⁷⁴ As stated by McDonald, “The theme of the tomb is timelessness: the decoration exclusively funerary. No references are made to any specific historic events or to anything that actually happened to Nefertari in her lifetime.”³⁷⁵ This in one sense serves in contrast to her life as a powerful sovereign. Nonetheless, her tomb is one of the most elaborate in The Valley of the Queens and Kings.

When walking into the tomb for the first time, though cliché, it was like stepping back in time to almost 3000 years ago. Aside from the modern lighting, the painted surfaces (520 square metres of them) were immaculately preserved.³⁷⁶ The wall paintings themselves cover all of the wall surfaces in the tomb, and have been a focus of conservation efforts by the Getty Conservation Institute over the past 30 years. The Getty first started work at the site in 1986 to clean and consolidate the wall paintings.³⁷⁷ This was because of the overall tomb composition due to limestone unsuited for wall paintings. Fracturing caused by earthquakes in the region and the flint bands in the stone composition made for a difficult surface to work with.³⁷⁸

A general summary of the wall painting procedure is shown below and adapted from:³⁷⁹

- Walls primed with gypsum
- Apprentice draftsmen (working in red) draw outline of text and images
- Master draftsmen (working in black) correct the work
- Sculptors carve the background as for designs to stand in relief
- Painters and varnishers paint over the carved design³⁸⁰

³⁷⁴ Ibid.

³⁷⁵ Ibid., 8.

³⁷⁶ McDonald, *House of Eternity*.

³⁷⁷ J. Paul Getty Trust, “Tomb of Nefertari (1986–1992),” accessed July 10, 2017, http://www.getty.edu/conservation/our_projects/field_projects/nefertari/.

³⁷⁸ McDonald, *House of Eternity*, 6.

³⁷⁹ McDonald, *House of Eternity*.

³⁸⁰ Ibid.

The paints used by the ancient Egyptians were mineral based paints limited to only primary colours.³⁸¹ Additionally, the binder used was gum Arabic, which can become damaged by UV rays.³⁸²

The tomb has been closed to the public many times since its discovery because of the continued negative effects of tourists.³⁸³ The tourists affect the humidity in the tomb, which damages the wall paintings. This is because of the presence of salts within the limestone. When moisture is added to these salts, they emerge and crystalize onto the painted surfaces, thereby damaging them.³⁸⁴ Therefore, conservation initiatives by the Getty have been focused on cleaning the paintings of dirt and salts in order to ensure their continued longevity.³⁸⁵

KV62: Tomb of Tutankhamen

KV62: Tomb of Tutankhamen, was discovered in November 1922 by famed Egyptologist Howard Carter.³⁸⁶ It dates back to the New Kingdom of the 18th Dynasty and is famous for the vast amount of treasure that was uncovered in the tomb and the overall difficulty of finding it.³⁸⁷ As it is located right underneath the entrance ramp of KV9, debris from the digging of that tomb was buried on top of its entrance.³⁸⁸ The tomb was filled completely with treasure, which was a rare occurrence, as most of the other tombs had been looted in antiquity. The contents of the tomb are now displayed in the Cairo Museum.³⁸⁹

³⁸¹ Ibid.

³⁸² Ibid.

³⁸³ Ibid.

³⁸⁴ Ibid.

³⁸⁵ Ibid.

³⁸⁶ Kent R Weeks, *The Illustrated Guide to Luxor: Tombs, Temples, and Museums* (Cairo, Egypt: American University in Cairo Press, 2005), 248-253.

³⁸⁷ Theban Mapping Project, "KV 62 (Tutankhamen) - Theban Mapping Project," accessed July 9, 2017, http://www.thebanmappingproject.com/sites/browse_tomb_876.html.

³⁸⁸ Ibid.

³⁸⁹ Weeks, *The Illustrated Guide to Luxor*.

KV62 is also the smallest of all of the royal tombs in the Valley of the Kings. I, like most tourists, expected it to be bigger and more elaborate. Some Egyptologists theorize that because Tutankhamen died unexpectedly and at such a young age, the tomb that had been intended for him was not far enough along to be used.³⁹⁰ The only decoration in the tomb is four painted surfaces in the Burial Chamber. As Weeks states, “the figures here are rather hastily done and ill-proportioned.”³⁹¹ This is in stark contrast to the painted surfaces of QV66, as those are elaborately detailed, though, the two tombs were designed in different dynasties. From investigation done by the Getty, “the condition of the paintings is excellent.”³⁹² The rest of the walls in the tomb are bare and rock cut, with tool marks identifying how the ancient Egyptians carved these final resting places for their rulers.

The tomb itself contains four main chambers (Antechamber, Annex, Burial Chamber, and Treasury) and an entrance corridor. Today, when visitors enter the tomb, they walk down a flight of steps and into the entrance corridor. This corridor leads into the Antechamber, which houses a climate controlled glass case containing the mummified remains of Tutankhamen. To the front left of the antechamber is the Annex, and to the right is the Burial Chamber, which contains Tutankhamen’s sarcophagus. The Burial Chamber is connected to the Treasury, which holds the seals that were broken when the tomb and burial chamber were uncovered. The Getty Conservation Institute has been working at the site since as a part of the conservation initiative since 2009.³⁹³ The work has involved aspects such as conducting research in order to understand the conditions

³⁹⁰ Ibid.

³⁹¹ Ibid.

³⁹² Getty Conservation Institute, “Conservation and Management of the Tomb of Tutankhamen: Conservation Planning and Implementation,” March 2013, http://www.getty.edu/conservation/our_projects/field_projects/tut/planning.html.

³⁹³ Getty Conservation Institute, “Conservation and Management of the Tomb of Tutankhamen:,” October 2013, http://www.getty.edu/conservation/our_projects/field_projects/tut/related_mats.html.

of the tomb and wall paintings, testing and evaluation of interventions, infrastructure upgrades, and the eventual dissemination of results to the general public.³⁹⁴

Because of a flood in 1994, a sheltered area outside the tomb was constructed, along with metal doors at the top and bottom of the corridor as a conservation strategy.³⁹⁵ There is also a fault line running through the tomb, as seen in the orthophoto below of the Burial Chamber Roof, but is in stable condition.³⁹⁶

Figure 9.3: Orthophoto showing fault line in ceiling of Burial Chamber
Image produced by author. Used with permission from The Getty Conservation Institute

³⁹⁴ Ibid.

³⁹⁵ Theban Mapping Project, “KV 62 (Tutankhamen) - Theban Mapping Project.”

³⁹⁶ Ibid.

Identified Heritage Values

As the two tombs are within a UNESCO World Heritage Site, they have “outstanding universal value” to all of humanity.³⁹⁷ Ancient Thebes with its Necropolis was designated in 1979 due to criterion (i), (iii), and (vi).³⁹⁸ The rationale behind these criteria is noted in the 1979 Advisory Body Evaluation for the site.³⁹⁹ The justification for criteria (i) is that: “The Thebian necropolis ‘relinquish nothing in importance or beauty to these monuments...the Valley of the Kings (1,500 B.C. to 1,000 B.C.) among which is that of Tutunkhamun, The Valley of the Queens, where, among others Nephertari, wife of Ramses II....are entombed.”⁴⁰⁰ For criterion (iii) the justification is because “The few examples which remain among these splendid monuments serve to attest to the antiquity, the unique and unequaled character of these monumental Thebian ensembles.”⁴⁰¹ Finally, for criterion (vi): “The monumental and archaeologic complex of Thebes with its temples, tombs, and royal palaces...constitute the material witness of the aggregate history of the Egyptian civilization from the Middle Kingdom to the beginning of the Christian era.”⁴⁰² In regards to values associated with the tombs of Nefertari, and Tutankhamen in particular, the following have been identified:

- The significance of the tomb pattern with turns and stairways symbolizing the “crookedness of the beyond”;⁴⁰³ (Figures 9.4 and 9.5)

³⁹⁷ UNESCO World Heritage Centre, “The Criteria for Selection.”

³⁹⁸ These criteria are as follows: “(i) to represent a masterpiece of human creative genius”, “(iii) to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared”, “(vi) to be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance.” Ibid.

³⁹⁹ ICOMOS, “ICOMOS Advisory Body Evaluation- World Heritage List- Ancient Thebes with Its Necropolis,” April 6, 1979.

⁴⁰⁰ Ibid.

⁴⁰¹ Ibid.

⁴⁰² Ibid.

⁴⁰³ McDonald, *House of Eternity*.

- Craftsmanship and artistry of the painted surfaces of the tombs;⁴⁰⁴ (Figure 9.6)
- Evidence of tomb construction through chisel marks;⁴⁰⁵ (Figure 9.7)
- The current state of conservation considering the 3000 plus years of weathering.⁴⁰⁶ (Figure 9.8)

Figure 9.4: Schematic floor plan of QV66: Tomb of Nefertari illustrating the turns and stairways in the tomb pattern
Used with permission from The Getty Conservation Institute

⁴⁰⁴ Ibid., 30.

⁴⁰⁵ Ibid., 29.

⁴⁰⁶ Getty Conservation Institute, "Conservation and Management of the Tomb of Tutankhamen: Conservation Planning and Implementation."

Figure 9.5: Schematic floorplan of KV62: Tomb of Tutankhamen illustrating the turns and stairways in the tomb pattern
Used with permission from The Getty Conservation Institute

Figure 9.6: Orthophoto of Burial Chamber rear wall in KV62: Tomb of Tutankhamen
This images shows an example of the artistry and craftsmanship within the tombs. Image produced by author. Used with permission from The Getty Conservation Institute

Figure 9.7: Chisel marks representing the remains of the tomb construction process
Used with permission from The Getty Conservation Institute

Figure 9.8: Orthophoto of wall surface C_Left in QV66: Tomb of Nefertari showing the current state of conservation
Image produced by author. Used with permission from The Getty Conservation Institute

Documentation Methodology

The documentation methodology consisted of four sections: the planning phase, on site recording, data processing, and information dissemination.

Figure 9.9: Documentation Methodology

Planning

The primary way in which planning was done was through researching about the areas that we would be recording. Information was provided to us from the Getty Conservation Institute, which consisted of contextual photographs, floor plans, and cross sections of QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen. The following equipment was brought with us from Canada for the survey:

- Nikon D800 camera and Lenses
- Ricoh Theta camera
- Leica TS 11 Total Station
- Faro Focus 3D Scanner
- Nikon Camera Flashes
- Photography Tripods and Umbrellas
- Portable LED work lights
- White Sheet
- Colour/Grey Card
- Rechargeable AA batteries

On Site Recording

The following recording techniques were used to capture information about the site. This case study takes on a bit of a different approach from the first two, as its focus is on how terrestrial photogrammetry was used during the recording process, and the constraints and difficulties encountered.

Figure 9.10: On site recording workflow

Total Station Survey

In order to establish a local coordinate system on site, the total station was used to capture control points for both the photogrammetry and laser scanning. These sites did present a bit of a challenge in regards to where to position these control points. As the wall surfaces were character-defining elements, under no circumstances could paper targets or tape be placed on them. Instead, they were positioned on built up infrastructure such as wooden walkways and stairs to be surveyed using a mini-prism on a rod. Flashlights were used in the tombs to identify the laser beam from the total station (Figures 9.11 and 9.12). The low lighting levels in the tombs impacted the ability of the team members to see the control points.

Figure 9.11: Example of shining a flashlight onto the survey control point
Used with permission from The Getty Conservation Institute

Figure 9.12: Author using a flashlight to identify the control point location (paper target control points in background)
Used with permission from The Getty Conservation Institute

Another interesting point to note is how cell phone photo-editing applications were used in the total station survey. The application allows for the user to first capture images, and then edit them on the phone by drawing on top of them using a stylus pen or finger. This made it a very useful tool for identifying the exact areas where natural control points were taken as the user could first identify the area with a contextual photograph, and then zoom in for a more precise photo to mark the exact location and number of the control point. This methodology is shown in Figure 8.14. Using the cell phone photo-editing application helped for the photogrammetric data processing, as the team did not have to mark the control points on a separate drawing of each façade. This would have been a cumbersome process. Instead, we were able to capture photographs and then upload them to the computer to be used for reference at the end of each working day.

Figure 9.13: Edited cell phone images for natural control point locations

The left image shows the contextual view marking the general location of the control point. The right image shows a zoomed-in view of the precise location and the control point number. Image produced by author. Used with permission from The Getty Conservation Institute

Laser scanning

Laser Scanning was used in order to create a point cloud of the tomb and surrounding areas for the creation of topographic maps, floorplans and cross section drawings. The Faro Focus X330 was once again used to complete this task (Figure 9.14). Paper targets were used as control points in the scans as a way to provide control points to the scans so it could be registered in the same local coordinate system as the total station survey.

For scanning, because the sites were open to tourists, it was important to get more overlap than necessary because tourists would appear in the scans. Therefore, the scans were all cleaned in Faro SCENE during the data processing stage to ensure that only the tomb areas were shown in the final consolidated point cloud.

Figure 9.14: Laser scanning set up in Burial Chamber K in QV66: Tomb of Nefertari
Used with permission from The Getty Conservation Institute

Photogrammetry

When capturing images for photogrammetry, the team abided by the CIPA 3x3 Rules to ensure at least 80% overlap between the images.⁴⁰⁷ The photographs were taken with the Full Frame Nikon D800 camera.⁴⁰⁸ 50mm and 20mm lenses were used depending on the distance to the surface. For each wall surface, the photographs were taken in a systematic way. We would take one strip of images from a distance away from the wall where the entire vertical surface could be seen in the camera lens. Then, from a closer vantage point, three more strips were taken focusing on the top, middle, and bottom of the walls respectively. When taking the photographs, it was important to ensure that the same detail could be seen in at least four or more respective images, which would help aid in the photogrammetric image registration. All of the images taken on site were .NEF (raw) format.

Photography in Difficult Lighting Conditions

The interest in discussing photography in greater detail in this case study is because of the strategies employed to capture highly detailed images while counteracting the effects of the poor lighting conditions in the tombs. The main light source inside the tombs was from fluorescent lighting boxes on the ground and shelf surfaces. This made for very uneven lighting across the surfaces that were to be photographed.

The main strategy implemented was the use of strobe lights (Figures 9.15 and 9.16). A flash trigger on the camera would cause the strobe lights to trigger, thereby providing even lighting to the surface of interest. Depending on the surface being photographed, the flashes would be placed either on the ground, on tripod stands, or held manually. They were aimed at an opposite

⁴⁰⁷ Waldhäusl and Ogleby, “3 X 3 Rules for Simple Photogrammetric Documentation of Architecture.”

⁴⁰⁸ Nikon, “Nikon | Imaging Products | Specifications - Nikon D800/D800E,” accessed July 20, 2017, <http://imaging.nikon.com/lineup/dslr/d800/spec.htm>.

wall surface to the one being photographed to bounce the light off of that surface, thereby diffusing it.

*Figure 9.15: Author taking photographs in QV66: Tomb of Nefertari
Used with permission from The Getty Conservation Institute*

*Figure 9.16: Strobes placed on right shelf surface to bounce light and illuminate left surface
Used with permission from The Getty Conservation Institute*

Umbrellas were another method used to diffuse the light, as seen in Figure 9.17 and 9.18. They were attached to the tripod stands or manually held as a way to diffuse the light onto the surface, versus the direct light of the flash. They were positioned towards the surface of interest, so the light would diffuse through them.

Figure 9.17: Example of typical umbrella setup when taking photographs
Photograph taken in Chamber C of QV66: Tomb of Nefertari. Used with permission from The Getty Conservation Institute

Figure 9.18: Manually held umbrella lighting strategy
Used with permission from The Getty Conservation Institute

For capturing ceiling surfaces, a white sheet was placed on the floor. This is shown in Figure 9.19. Strobe lights were aimed directly at this white sheet in order to help diffuse the light upwards towards these ceiling surfaces, thereby providing even lighting.

Figure 9.19: Example of ceiling photography strategy with use of white sheet and manually held strobes
Used with permission from The Getty Conservation Institute

Raking Light

Raking light photography was done for areas identified by Getty Conservation Institute team members. The methodology involved taking successive images of the same area, while moving a hand-held strobe flash in approximately 30-degree intervals around the surface of the wall. This would allow for light to hit the surface from different angles, thereby producing a range of different visual interpretations than if the light was only provided from one single source (Figure 9.20). Based on the various images, wall painting conservators from the Getty Conservation Institute can interpret them in order to understand the condition of the wall surfaces.

Figure 9.20: Example of raking light panel for Burial Chamber K in QV66: Tomb of Nefertari
Used with permission from The Getty Conservation Institute

Macro Photography

The use of macro photography was also done in areas identified by the Getty Conservation Institute team members. They were photographed with a 20mm macro lens at a very close range—only a few inches from the wall surface. The purpose of these images was to document conditions found on these surfaces to identify the pathologies. Specifically, photographs were taken of areas of salt crystallization (Figure 9.21) and plaster cracking (Figure 9.22).

Figure 9.21: Salt crystallization in Rear Side Chamber Q Ceiling in QV66: Tomb of Nefertari
Used with permission from The Getty Conservation Institute

Figure 9.22: Plaster cracking on Descending Corridor I ceiling in QV66: Tomb of Nefertari
Used with permission from The Getty Conservation Institute

Site Restrictions

When doing the recording on site, the biggest restriction that impacted the work were the presence of tourists as seen in Figure 8.24. Photography was stopped when tourists were in the tomb because the flashes would negatively affect their viewing experience, and out of respect to that, we did not take any photographs. In terms of laser scanning, tourists did end up in some of the scans, resulting in more post-processing time cleaning the scans. Overall, there were many more tourists in KV62: Tomb of Tutankhamen than for QV66: Tomb of Nefertari.

Figure 9.23: Pano-tour screenshot of tourists inside KV62: Tomb of Tutankhamen
Used with permission from The Getty Conservation Institute

Data Processing

Laser Scanning Registration

The laser scans were processed by Professor Mario Santana in Faro SCENE. When reviewing the point cloud file in Autodesk ReCap, I noticed that there were occlusions in the final point cloud model on both the floor and ceiling areas of the scans. The black lines as seen in Figures 9.24 and 9.25 illustrate these occlusions. We do not know why this was the case, but the scanner was sent in for calibration shortly after the mission to try and fix the issue.

Figure 9.24: View of floor occlusion (represented by black line)
Screenshot by author in Autodesk ReCap

Figure 9.25: View of ceiling occlusion (represented by black line)
Screenshot by author in Autodesk ReCap

Orthophoto Generation

The workflow that used to generate the orthophotos and their respective PDF layouts is shown in the figure below.

Figure 9.26: Orthophoto processing workflow

Image Processing

Before the images could be used in the creation of the photogrammetric model, they had to be renamed and calibrated in Adobe Bridge and Photoshop. Parameters such as temperature (white balance), exposure, highlights, and shadows were adjusted in each image. The most important variable was the temperature, as it was essential to ensure that all of the surfaces in each chamber had the same colour consistency. This was accomplished through taking a photograph in each chamber with a team member holding a color card (Figure 9.27). The colour card was used as a reference to determine the correct temperature and hue of each chamber. Once colour corrected, the images were converted into .JPG files from the original raw NEF format (Figure 9.28).

Figure 9.27: Colour card image
Used with permission from The Getty Conservation Institute

Figure 9.28: Example of photographs before and after colour correction
Used with permission from The Getty Conservation Institute

Photogrammetric Processing

PhotoScan was used to generate the orthophotos. The PhotoScan workflow as explained in Chapter 4, was used to process the data.

Masking the images was an essential step in this project because in many of the wall surfaces there were objects or barriers in the way of the photographs. One area in particular that this was an issue was for the lower walls surfaces of Descending Corridor I in QV66: Tomb of Nefertari. This was because an immovable barrier was blocking the view of the paintings, as seen in Figures 9.29 and 9.30. Therefore, the team took photographs with views in-between and above the balusters as a way of capturing the whole surface. The railings were then masked in PhotoScan.

Figure 9.29: Painted surfaces blocked by immovable wooden barrier
Used with permission from The Getty Conservation Institute

Figure 9.30: Photograph from above railing to capture blocked details
Used with permission from The Getty Conservation Institute

The dense cloud was processed on a medium setting, which was sufficient for creating a high quality model due to full-frame image sizes (7360x4912 pixels).

After the mesh was created, it was edited to include only the wall surface of interest and not any of the adjacent wall surfaces. This was an important step, because the orthomosaic process applies the images taken directly to the mesh surface. This means that in unedited meshes, photos from the adjacent surfaces would end up being superimposed onto the generated orthophoto, which was not what the team was looking for as a final product.

One deviation from the workflow defined in Chapter 4 was how scale was provided to the individual photogrammetric wall surfaces. This referencing was done after the dense cloud had

been generated because of the very high level of overlap between the images, and that the control points did not have an impact on aligning the photographs. As we did not measure control points on each wall surface, a new methodology was developed which involved the use of the 3D point cloud generated from laser scanning. The point cloud model was referenced according to local control points taken on site, which therefore meant that each individual point in the point cloud was correctly georeferenced. These georeferenced points were taken from the model in Autodesk ReCap by using the note command. When using this command, users are able to click on individual points and see what their respective X, Y, and Z coordinates are. These values were copied into a text file, which was imported into PhotoScan to serve as the references. It was important that the same point that was selected in the point cloud was also selected in the images of the photogrammetric model, which is seen in Figure 9.31. The naming conventions also had to be the same in the text file and photogrammetric model. Three or more well distributed points were taken for each surface.

Figure 9.31: Similar points selected in the ReCap file (left) and the PhotoScan project (right)
Used with permission from The Getty Conservation Institute

The last step in the methodology was the creation of the orthomosaic images. As the software automatically stitched together the images based off of the photos used to generate the

model, there were some instances of where manual editing of those areas was required. Figure 9.32 shows a typical example of how problem areas were selected and then specific parts of images were applied to them in order to get the correct visual representation. The area of interest is illustrated by a red polygon shape. The final orthophotos were then exported as .tiff files to be used in the drawing set layout.

Figure 9.32: Before and after orthomosaic cleaning
Screenshots by author from PhotoScan. Used with permission from The Getty Conservation Institute

As a subsection to the macro photography application, close range photogrammetry was also performed in identified sections by the Getty Conservation Institute team members to get a better understanding of crack patterns and damages. The difference between the orthophoto of normal photogrammetry and close range is show in Figure 9.33. The images have approximately the same scale to show the differentiation.

Figure 9.33: Difference between normal and close range photogrammetry for wall C_Front_Right in QV66: Tomb of Nefertari
Used with permission from The Getty Conservation Institute

Preparing layout for Drawing Set

The end product of the project was the creation of a drawing set in AutoCAD of all of the scaled orthoimages. When the images were brought into AutoCAD, they had no scale. This is because PhotoScan does not have a scale bar when exporting orthoimages. An alternate strategy was used, whereby the images were aligned with the point cloud model of the tomb to obtain the highest level of accuracy in regards to scaling the image. Two AutoCAD files were used; one to manipulate the point cloud and scale the drawing, and the other, which contained all of the scaled images. This was an efficient workflow because if the point cloud and orthoimages were in the same file, it would be confusing to keep manipulating the view of the point cloud, which would therefore affect the view of the orthoimages. Additionally, during plotting of the images, it was important to remember to set the visual style to 2DWireframe to ensure that the images were plotted at their full resolution. The view is normally set to wireframe in order to view the point cloud and view compressed images, which makes the software run faster because of the large uncompressed image sizes.

Deliverables: Drawing Set of Orthoimages and Digitally Assisted Condition Mapping using Virtual Reality

The final deliverables for this project were twofold- the generation of a drawing set containing scaled orthoimages of the wall surfaces of the tombs, and a digitally assisted condition mapping application through the use of virtual reality technology. Sample sheets from the drawing set are shown in Appendix D. As the drawing set procedure was described above, this section will focus solely on the development of a virtual reality environment based off of the information that was created as a part of the photogrammetric process.

Digitally Assisted Condition Mapping using Virtual Reality

The goal of using virtual reality for condition assessment mapping tries to solve the gap of information dissemination. Time spent on site is incredibly valuable, especially in projects that involve international travel. As such, this deliverable was designed for the application of being able to assess the current conditions in KV62: Tomb of Tutankhamen, without actually being there. These conditions are based off of the photogrammetric information generated as a part of the orthophoto creation process.

Methodology

The virtual environment focuses on the Annex, Antechamber, Burial Chamber, and Treasury, and was developed with help from Isaac Baronikian; an undergraduate student in Architectural Conservation and Sustainability Engineering at Carleton University. I held a supervising role in the creation of the virtual reality environment and provided insight into what the final outcome was to be.

The game engine used to design the virtual environment was Unreal Engine 4, by Epic Games.⁴⁰⁹ From the literature review in Chapter 5, this was one of the game engines recommended for use in academia. As well, as it was being used by other members of the CIMS Lab for their own projects, they could be used to help with potential troubleshooting.

The methodology for the generation of the virtual environment first involved decimating the meshes of the wall surfaces in each of the four chambers to be included. This step was necessary because the full size models would have been too large in regards to file size to effectively run in a virtual environment. This step was also done in the literature consulted in Chapter 5. The polygon count for the meshes was set to 500,000— an approximate number that was decided upon through trial and error. The models were then textured using the 4096x2 parameter to ensure a realistic texture. These models were then exported as .fbx files to be imported into Unreal Engine. When the models were imported, the insertion point was very far away from the actual model, and the model could not be seen due to scaling difficulties.

An intermediate step was done in order to solve this problem, whereby the .fbx files were brought into Rhinoceros software to establish the new origin point to hopefully resolve the scaling issue.⁴¹⁰ Each wall of the chamber was brought into Rhinoceros separately, shown in Figure 9.34, but they all had the same origin point for ease of geometric relationships between the wall surfaces.

⁴⁰⁹ Epic Games, Inc, “Unreal Engine | Blog,” accessed July 21, 2017, <https://www.unrealengine.com/en-US/blog>.

⁴¹⁰ Robert McNeel & Associates, “Rhinoceros,” accessed July 21, 2017, <https://www.rhino3d.com/>.

Figure 9.34: View of model in Rhinoceros
Screenshot by author

The wall surfaces were then saved as a .3dm Rhinoceros proprietary file before being resaved again as .fbx. They were then imported back into Unreal Engine. The scale was set to 100, because even though the model was referenced in PhotoScan in metres, Unreal Engine works in centimeters. This methodology solved the original problems, and the textured mesh successfully loaded into the virtual environment. Further refinement of the visual aspect of the environment was done, as well as the creation of a colour coded key map that was placed in the center of the room to understand what chambers in the tomb the user is viewing.

The virtual environment was initially designed for wall painting conservators from the Getty. The way in which the virtual reality experience was designed to take place is through being able to analyze each wall surface individually, as to fully be immersed with that particular wall surface instead of the tomb in its entirety. This has to do with software experimentation in regards to the way in which the tomb walls can be visualized. This enables for users to see the ceiling surfaces at eyelevel instead of having to look up to see their current state.

The headset used for the immersion portion of the virtual reality experience was the HTC Vive- another headset mentioned in the literature explored.⁴¹¹ The HTC Vive has a 110 degree field of view, with 360 degree motion tracking due to the use of two sensors placed around the room.⁴¹² It contains handheld controllers as a way of easily moving from one location to the next within the virtual environment.⁴¹³ The one potential drawback to using this type of headset is that it is connected to the computer. The Vive website does say that a standalone VR system is coming out later this year.⁴¹⁴

Screenshots of the final virtual environment are shown below, along with a few photographs of the author testing out the system.

Figure 9.35: Annex wall surfaces in the virtual environment
Screenshot by author

⁴¹¹ HTC Corporation, “VIVE™ Canada | Discover Virtual Reality Beyond Imagination,” accessed July 21, 2017, <https://www.vive.com/ca/>.

⁴¹² Ibid.

⁴¹³ Ibid.

⁴¹⁴ Ibid.

Figure 9.36: Burial Chamber wall surfaces in the virtual environment
Screenshot by author

Figure 9.37: Antechamber wall surfaces in virtual environment
Screenshot by author

Figure 9.38: Treasury wall surfaces in virtual environment
Screenshot by author

Figure 9.39: View of virtual environment
Screenshot by author

Figure 9.40: View of virtual environment
Screenshot by author

Figure 9.41: Bird's-eye view of virtual environment
Screenshot by author

Figure 9.42: Author testing out virtual reality environment with view of what he is seeing on the computer in the background
Photograph credit- Isaac Baronikian, used with permission

Figure 9.43: Author testing out virtual reality environment with view of what he is seeing on the computer in the background
Photograph credit- Isaac Baronikian, used with permission

Chapter Summary

The documentation work at QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen focused on the use of photogrammetry and laser scanning to document the tombs. Photogrammetry was of particular interest in this case study, as the final outcome was the production of high resolution orthophotos of the wall surfaces. Lighting strategies such as strobes and umbrellas had to be incorporated to ensure even lighting across each wall surface being documented. The processed data from the photogrammetric stages was also developed into a digitally assisted condition mapping application. The original idea was that it could be used by wall painting conservators from the Getty to be able to analyze the wall paintings in an immersive environment. Unfortunately, this did not end up being the case, as the resolution of the headset was too low to be able to identify the fine detailing of the wall paintings.

Chapter 10: Discussion of Case Studies and Research Findings

Each of the case study sites provided different research findings in regards both gaining an understanding of documenting historic sites and solving gaps of this thesis. Therefore, the first part of this chapter will provide a summary of: 1) workflows developed at each case study, 2) the skill levels required to apply these approaches, 3a) the project timeframe, and 3b) an anticipated timeframe if the project was done using the information acquired throughout this research.

1) Developed Workflows

Figure 10.1: The Log Farm Documentation approach

Prince of Wales Fort Documentation Approach

Figure 10.2: Prince of Wales Fort Documentation Approach

**QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen
Documentation Approach**

Figure 10.3: QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen Documentation Approach

2) Skill Levels required to apply Documentation Approaches

Three different skill levels have been established by the author to describe the level of expertise required to complete the workflows that were established in this research.

Low- Able to complete the task with no or limited knowledge of the recording techniques, or can complete the task with the assistance of someone who has a medium to high skill set.

Medium- Is familiar with using the digital recording techniques and software on their own, and can produce basic deliverables accordingly. Individuals who have completed courses about digital recording techniques would be an example of those having a medium skill set.

High-Specialized skill set requiring more experience than in the medium level. A high skill level task would move beyond the basic deliverables for the production of outcomes for more advanced analyses.

Table 10.1: The Log Farm Documentation Skill Levels

The Log Farm Technical Skill Levels required to apply the developed workflow		
	Skill Level	Justification
Total Station Survey (Leica TS06)	Low to Medium	The difficulties a user may encounter are levelling the total station and setting up the project. Therefore, this is considered a medium level skill set. The surveying of control points is considered a low level skillset because the workflow involves orienting the laser to the control point and surveying it- a task that does not require as much expertise as setting up the project.
Photogrammetry (Photography and the use of PhotoScan for processing)	Low	Photography principles for photogrammetry are straightforward and easy to understand. For data processing, PhotoScan is considered to be a low skill level technique because of the high usability aspect of the program and the workflows used to process the images.
Laser Scanning (Faro Focus X330)	Medium	There is a need for the user to understand where to position the laser scanner to optimize the concept of scan overlap during registration. As well, the user needs knowledge of target positioning to register areas that do not have high overlap percentages.

Faro SCENE Processing	Medium	The software requires training to understand the workflow to register the scans, let it be of top based, cloud to cloud, or target based.
Autodesk ReCap	Low	Program has a high degree of usability because of the relative ease of importing projects, cleaning point clouds, and viewing point clouds.
Autodesk Revit	Medium to High	A strong skill set in Revit is required to model the geometrically complex elements. The medium skill set is representative of generating a model showing basic element geometries and material edits, whereas a high skill set is based on modelling the elements directly as seen in the point cloud and with texture as seen in the point cloud.

Table 10.2: Prince of Wales Fort Documentation Skill Levels

Prince of Wales Fort Technical Skill Levels required to apply the developed workflow		
	Skill Level	Justification
UAV Photography (DJI Phantom 4)	Low	Commercially available UAVs such as the Phantom 4 have a very high degree of usability, as the author only had two days of training before conducting the flights in Churchill. The ability to take photographs with the UAV was also a low skill level task, as all the user has to do is press a special button on the controller to capture the image.
Photogrammetry Processing-PhotoScan	Low to Medium	The large number of images used presented some difficulties with using the software, thereby making it a medium level skill set in this case study. Also, an understanding of the exif data of the images is required to ensure that they are aligned correctly.
Photogrammetry Processing-ContextCapture	Low to Medium	The workflow for the creation of photogrammetric models requires a low skill set, as this software is presented in a systematic way as to complete the photogrammetric models. It can be a medium level technique because of the background knowledge required to import the camera parameters.
CloudCompare Deformation analysis	Low	This is a low skill level software, as the user only has to import the point cloud file and apply best fit primitives.
Autodesk AutoCAD	Low to Medium	Tracing of Orthophotos is considered as a low level task, but the importing and scaling of the orthophoto based off of the point cloud requires more knowledge and expertise.

Table 10.3: QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen Documentation Skill Levels

QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen Technical Skill Levels required to apply the developed workflow		
	Skill Level	Justification
Photography for Photogrammetry	Medium to High	A strong understanding of lighting strategies for difficult lighting strategies can only be gained by years of experience. The actual image acquisition still required a medium level of photography in order to produce the desired results of the client.
Total Station Survey	Medium	Control points had to be carefully chosen due to the tight spaces and stairways. The surveying in this case study requires a higher skill level than when surveying in open spaces like at The Log Farm.
Laser Scanning	Medium	An understanding of scanner locations was especially important to ensure that there are no occlusions in the final model, which requires a medium skill level.
Photogrammetry Processing- PhotoScan	Low to Medium	A low skill set is required to mask the images and complete the alignment, dense cloud, and mesh stages. A medium skill set is required because of the way control points were selected and the cleaning of the orthophotos.
Faro SCENE Processing	Medium	The software requires training to understand the workflow to register the scans, let it be of top based, cloud to cloud, or target based. This makes it a medium skill level technique.
Autodesk AutoCAD	Low to Medium	Final drawing sheet layout of Orthophotos is considered as a low level task, but the importing and scaling of the orthophoto based off of the point cloud requires more knowledge and expertise.
Virtual Reality- Unreal Engine 4	Low	There are some troubleshooting issues with importing models into Unreal Engine. The software had a high degree of usability and interactivity for the creation of virtual environments with a non-existent to limited initial knowledge base

3a) Project Timeframes

Table 10.4: The Log Farm Project Timeframe

The Log Farm Project Timeframe		
Recording		
	Number of Working Days	Explanation of Work
Site Visits for contextual information	3	Visits were conducted approximately once every two weeks for half day time periods. 6 total visits were conducted, equaling 3 working days
NCC Visits for archival information	1	Two half day visits were made to the NCC offices to review archival material.
Photogrammetric Survey (includes total station survey)	1	One day was required for conducting the photogrammetric survey. Half the time was spent doing the total station survey, while the other half involved taking photographs
Laser Scanning Survey	3	Three days were required for the laser scanning survey. A half-day during the first scanning day was used for the total station survey
Data Processing		
	Number of Working Days	Explanation of Work
Photogrammetric processing in PhotoScan	5	The typical PhotoScan process was followed to produce the photogrammetric models. Low, medium, high, and ultra-high quality dense clouds were created. Process would have been 3-4 working days if ultra-high model was not required due to the processing time.
Laser Scan Registration in Faro SCENE	25	Registered and aligned the raw scans for the creation of two separate point clouds. The point clouds consisted of one contextual point cloud that was uncleaned and the other of The Bradley House that was cleaned. Both models were in the same local coordinate and exported as ReCap project files.
ReCap processing	3	For the Bradley House scans, cleaning of the facades was required as the ultra-high dense cloud created through photogrammetry was used for the exterior view. The portions that were kept of the exterior laser scans were the terrain so it could be included in the point cloud.
Production of Deliverables		
	Number of Working Days	Explanation of Work
BIM	10	Creation of BIM for The Bradley House. This process also involved watching tutorial videos of Revit, reading Carleton Immersive Media Studio Revit protocols. As this was done during the final stages of the thesis research, time and my own skill set with Revit was a factor in the final model production. Therefore, only a basic geometric representation of the building has been created.

Table 10.5: Prince of Wales Fort Project Timeframe

Prince of Wales Fort Project Timeframe		
Recording		
	Number of Working Days	Explanation of Work
Special Flight Operations Certificate (SFOC)	6 (4 days creating own SFOC, 2 days filling out template)	Created own SFOC to submit to the Prairie and Northern Region of Transport Canada only to discover that this region has a template to fill out to submit the form, thereby making the process quicker.
On Site UAV Photogrammetry	3	Twelve flights were conducted over the course of three days to aid in the capturing of images for a photogrammetric model of the Fort and its surrounding area to aid in the conservation initiative on site.
Data Processing		
	Number of Working Days	Explanation of Work
Photogrammetric processing (Joint approach between using PhotoScan and ContextCapture)	60 (50 PhotoScan, 10 ContextCapture)	Time in this phase was spent first determining a strategy of how to align the images so they would be in their correct locations, especially since the exif data did not aid in the image alignment process. Once aligned, time was also spent processing the models, which would take up to 2 days when processed on a high quality setting in PhotoScan. Experimentation with generating the mesh from PhotoScan also made this phase take encompass a long time period. ContextCapture was finally experimented with, which successfully solved the problem of mesh creation. The 10 days spent using ContextCapture encompassed developing the workflow, and generating a series of models (one of the Fort itself, and the other showing the Fort in its contextual environment). Included in this step was also the merging of meshes in CloudCompare, which took less than half a day.
Photogrammetric processing for wall deformation analysis	4	Processed photogrammetric models from images from flight 10, which were those taken 3m away from the wall. High quality dense cloud models were created to be used in the deformation analysis component.
Production of Deliverables		
	Number of Working Days	Explanation of Work
Measured Drawing	4	Used AutoCAD to trace over the created orthophoto to identify the individual stones in the wall to be used for potential on-site monitoring.
Deformation Analysis in CloudCompare	3	Using the wall section point clouds, best fit primitives were applied to the model to allow a cloud to mesh analysis to measure the deformations.

Table 10.6: QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen Project Timeframe

QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen Project Timeframe		
Recording		
	Number of Working Days	Explanation of Work
On Site Recording	10 days	Total station survey, Photogrammetric survey, and laser scanning survey conducted during the time on site.
Data Processing		
	Number of Working Days	Explanation of Work
Photogrammetry (PhotoScan)	30	The creation of orthophotos for all of the wall surfaces within the tombs. This was accomplished using the typical PhotoScan workflow, with one small deviation in regards to providing scale to the models.
Production of Deliverables		
	Number of Working Days	Explanation of Work
Drawing set sheet layout	10	Importing and scaling of orthophotos in AutoCAD. Drawing sets were then prepared for each of the respective chambers.
Virtual Reality (PhotoScan, Rhinoceros, Unreal Engine 4)	15	Experimentation with Unreal Engine 4 in order to create the virtual reality environment of KV62: Tomb of Tutankhamen. This step also included decimating the meshes of the tomb wall surfaces in PhotoScan and importing them into Rhinoceros for proper scaling.

3b) Estimated Project Timeframe if work was redone using acquired knowledge

Table 10.7: The Log Farm estimated timeframe if done again

The Log Farm Project Estimated Timeframe if done again using acquired knowledge		
Recording		
	New Number of Working Days	Differences in Workflow
Site Visits for contextual information	3	Still would require the same amount of time in order to gain an understanding of the site and its values.
NCC Visits for archival information	1	Still would require the same amount of time for archival research.
Photogrammetric Survey (includes total station survey)	1	Still would require the same amount of time for the photogrammetric survey. The total station process would be quicker.
Laser Scanning Survey	3	Still would require three days for surveying. Scan resolutions would be changed to Outdoor less than 20m and more scan positions would be taken to ensure sufficient overlap to reduce the registration errors in Faro SCENE to below 5mm. As well, pinch point scans would be taken between adjacent rooms/interior to exterior spaces.
Data Processing		
	New Number of Working Days	Differences in Workflow
Photogrammetric processing in PhotoScan	5	The processing of the photogrammetric models would not change, as I previously had a strong skill set using PhotoScan.
Laser Scan Registration in Faro SCENE	10	The biggest difference would be the initial creation and organization of clusters as to ensure an accuracy below 5mm for the entire site. Additionally, understanding the concept of setting the control points to global origin would ensure that the model is referenced in the proper coordinate system. Finally, exporting the individual barn and house clusters as separate files referenced to the same coordinate system would cut down on the amount of registration time trying to align a large number of scans.
ReCap processing	2	Point cloud cleaning would take one less day than before due to the experience gained doing the technique already.
Production of Deliverables		
	New Number of Working Days	Differences in Workflow
BIM	20	The BIM still requires more work, as even though the basic model geometry of the house has been completed, the individual elements can be edited to include the textures as seen from the point cloud photographs, and further refining to make the model itself more visually appealing for representation purposes.

Table 10.8: Prince of Wales Fort estimated timeframe if done again

Prince of Wales Fort Project Timeframe if done again using acquired knowledge		
Recording		
	New Number of Working Days	Differences in Workflow
Special Flight Operations Certificate (SFOC)	2	This step would now only require filling out the SFOC template from the Prairie and Northern Region of Transport Canada.
On Site UAV Photogrammetry	3	The number of working days on site would stay the same, but the methodology used for image acquisition would change, as automatic image capturing would be tested.
Data Processing		
	New Number of working Days	Differences in Workflow
Photogrammetric processing (Joint approach between using PhotoScan and ContextCapture)	20 (15 PhotoScan, 5 ContextCapture)	Time in this phase would be cut down to 1/3 of what was originally spent. This would be because of the use of the developed workflow between PhotoScan and ContextCapture. The most amount of time would be spent masking images and identifying markers on all of the photographs instead of trying to ensure the proper alignment and mesh generation. The ContextCapture timeframe would be for the creation of the mesh models, which is an automated process that can be left to run overnight. Included in this phase is also the merging of meshes in CloudCompare, which would take less than half a day.
Photogrammetric processing for wall deformation analysis	4	This step would still require the same number of working days, as it involved the typical PhotoScan workflow.
Production of Deliverables		
	New Number of Working Days	Differences in Workflow
Measured Drawing	4	No differences in workflow, as the only factor in the creation of a drawing set of this nature is time tracing all of the individual stones.
Deformation Analysis in CloudCompare	3	No difference in workflow time because of the existing knowledge base of using CloudCompare.

Table 10.9: QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen estimated timeframe if done again

QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen Project Timeframe if done again using acquired knowledge		
Recording		
	New Number of Working Days	Differences in Workflow
On Site Recording	10 days	None- the team made the most out of their available time on site
Data Processing		
	New Number of Working Days	Differences in Workflow
Photogrammetry (PhotoScan)	30	None- the time spent processing the images would not have been different with the new knowledge acquired.
Production of Deliverables		
	New Number of Working Days	Differences in Workflow
Drawing set sheet layout	8	This deliverable would take less time because of the knowledge of scaling the orthophotos to the point cloud models. The sheet layout would still take the same amount of time.
Virtual Reality (PhotoScan, Rhinoceros, Unreal Engine 4)	10	This new workflow would take less time due to the familiarity with the process of importing texturized mesh models into Unreal Engine 4, and understanding how to create the virtual environment.

Common Parameters between Case Studies

The case study sites can also be analyzed according to a series of parameters that were common to all of them. The research gaps identified at the beginning of this thesis are revisited in order to generate final conclusions about the research process and to provide answers to the problem statement. The areas of discussion are:

- Site Accessibility/Constraints and Time Management on Site
- Recording Techniques used
- Data Processing
- Review of the Deliverables
- Dissemination of the documentation
- Methodologies if the recording was redone
- Learning Outcomes

Site Accessibility/Constraints and Time Management

The Log Farm presented many advantages for documentation. As the site was located in Ottawa, it was easily accessible by car whereas the other two sites, which could only be accessed by flight. This allowed for more contingencies when doing the work, allowing for return visits to collect additional data. In fact, a third scanning visit was required to help register the previous days' scans. The Log Farm was also an isolated site, with no tourists or public to impede the work. The one aspect that did slow down my progress were the barn cats. The cats would want to play with the spherical targets while I was scanning, sometimes moving them in the middle of a scan. Because the spheres would now be in different places in the scans they had to be redone. To solve this problem, I moved the cats into the Bradley House when I was scanning exterior areas, and brought them out of the house when surveying inside. Another issue encountered on site was the cold weather, as scanning was done during the winter. The scanner would periodically give an error message indicating that it was too cold to scan and then would shut off—once again interrupting the scanning process. In regards to time management, it was important to ensure that the equipment batteries were fully charged before going to site, as there was no power in the general area that was surveyed. Making the most out of your time is a very important characteristic of the recording process. Because of the ease of booking another site visit, it did not impact the workflow as much as the two other case studies.

The Prince of Wales Fort project illustrated working at an inaccessible site on a very tight timeframe. Because the Fort is located in Churchill, Manitoba, flight arrangements had to be made to get to and from Churchill, meaning that time was a factor. Once in Churchill, the team had to take a fishing boat across the Churchill River to the site each day, thereby presenting another constraint. This was because the times the boat could cross the river were dictated by the tides. If

any equipment was forgotten in the morning, it could only be brought back during high tide—something that could have hindered the working process. The unpredictable weather in Churchill was another obstacle that was faced when on site, as if there was any rain, the UAV could not fly. Because of this, time management was critical for recording on site. Each UAV flight was planned before so I knew exactly what area was to be surveyed, thereby getting the most out of the UAV battery life. Immediately after a flight was conducted, the battery was charged to be ready for another round of photographs. There were tourists on site, but they only came during certain times of the day. They did not interrupt the recording process as the UAV could fly in the areas where they were not standing. From the author's own experience, when dealing with the Prairie and Northern Region, they have a set template form to fill out. For the Ontario region, it is up to the individual to prepare their own set SFOC. Therefore, it is suggested that Transport Canada create some form of fast-track process, specifically when dealing with projects on National Historic Sites commissioned by the Heritage Conservation Services-Public Services and Procurement Canada.

For QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen, before the work could commence, planning such as background checks and flight booking had to be done well in advance of the project date. The unpredictability of travelling to Egypt with all of the equipment was another factor that was considered by the team. The laser scanner, total station, and DSLR cameras were taken as carry-ons on the flights, and the other equipment was split up amongst the checked baggage in such a way that if one of the bags were to get lost, there would be enough available equipment in the other two to still complete the survey. This did not end up being the case, as all of our equipment did make it safely to Luxor. Transportation was arranged by the Getty to and from our accommodations in Luxor. Managing time on site was especially critical due to the tight timeframe. After the work on site had been conducted, the team held a meeting in order to go over

what information had been captured that day, and what our plan was for the next. This helped to establish a schedule in order to make sure that everyone was on track and could complete their tasks in the time that we had available. The major constraint experienced on site was tourists, as previously stated. Therefore, to manage the effects of the tourists, we got to the sites at 7am each day to ensure at least a few hours of uninterrupted work before they would start to show up later in the morning.

Recording Techniques Used

In discussing the recording techniques used, it is imperative to state that there is no such thing as a good or bad recording technique—it is all about choosing the correct technique for the project. The Log Farm provided an opportunity low-stress environment in regards to using these digital recording techniques because the project did not have serious time constraints. Some conclusions were that photogrammetry worked best for capturing information of the exterior facades of the building, whereas laser scanning worked best in the interior spaces. Photogrammetry could have been used to document the interior of the Bradley House, but restrictions such as the tightly confined spaces and hallways would make the image capturing process more difficult. As well, bringing in the total station to survey control points would be challenging for those same reasons, and for the fact that the uneven floors made for difficulties levelling the total station. For laser scanning, the lack of paper targets set up during the surveying day was one of the main learning experiences. This was because the targets fell off of where they were positioned because of a combination of the cold weather and poor choice of tape. Therefore, a recommendation it to use more targets in the event that some fall off during the survey day, and using stronger tape, such as Gorilla Tape instead of Duct tape.

UAV Photogrammetry was the primary technique used at Prince of Wales Fort. This technique could capture a multitude of photographs in a limited amount of time. The biggest constraint was the camera sensor size and focal length. As the sensor was only a 1/2.3" sensor, the image quality was not as good as when using a DSLR with an APS-C or Full Frame sensor. Additionally, the large field of view resulted in too much overlap between the images. This made image masking even more important during the processing stage. This technique also presented some technical constraints, as I was new to flying UAVs and did not have much experience testing out the automatic image capturing applications like Pix4d. When I did use Pix4d during the UAV training day, the UAV would land after in the same location as where it had taken its last photograph and not return to the home position. This resulted in the UAV landing in a patch of grass and chewing up the propeller blades. As I did not want this to happen when in Churchill, images were collected manually. Another issue encountered during the recording phase was that there were periods of time on site where no work could be done because the batteries were still charging, thereby slowing down the data capturing process.

When working in Egypt, lighting conditions for photography was the biggest constraint faced in regards to the recording. A new lighting setup had to be established for each respective façade to ensure an even lighting across the surface when capturing the photographs. In regards to my own skillset, the biggest technical constraint faced was using manual focus when taking photographs. As I did not have much experience using manual focus, it provided a good learning experience to enhance that ability. The difficult part was ensuring that all of the photographs were taken at the same distance away from the wall surfaces, especially when taking images at the top and bottom strips, as I had to bend or reach in order to capture the photos which would bring the camera out of focus resulting in blurry images.

Data Processing

Each site again presented different constraints for the data processing aspect of the project, as the difficulties were based on what the specific deliverable was. For The Log Farm site, the difficulties encountered are shown below:

- When multiple scans were open at once in Faro SCENE, the computer would crash because of the hardware constraints;
- When registering the scans, sometimes two scans were being registered to one another when they shouldn't have (i.e. opposite sides of the barn tied together using scan data from trees or other far away objects, and not the building façade itself). This led to higher than acceptable errors (greater than 5mm);
- It was important to look at the accuracy values of registered clusters in SCENE very carefully, as the scan manager results can sometimes be deceiving. It may indicate a value in the yellow (medium/moderate error), but when expanding the section it would be green for all scans (error below 5mm);
- Surveyed points inside the Bradley house should have been used in order to help register the house scans to the whole farm, versus using cloud to cloud or spheres. There were many difficulties in this stage to align all of the scans together because of the low quality of the overlap.

The biggest difficulty faced for Prince of Wales Fort was generating a mesh from the images in PhotoScan. Due to the large number of images and hardware constraints of the computer used, PhotoScan was unable to generate the mesh. Therefore, ContextCapture was used to successfully complete this step by splitting the model into a series of tiles and generating the mesh in a piecewise manner. The final point cloud generated by ContextCapture also had a much higher point density than the one created in PhotoScan. Therefore, one conclusion that can be made is that ContextCapture is able to handle larger images sets better than PhotoScan. It does not allow the user to generate orthophotos, so if that is the final end product, a combination approach of the software should be used.

There were no constraints when processing the data for QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen, The only issue was determining a methodology to provide scale to each of chunks produced in PhotoScan, as control points were not measured for each wall surface.

This was accomplished by selecting points from the point cloud in ReCap that was in the correct local coordinate system and then choosing the same point in PhotoScan to reference those coordinates to.

Review of Deliverables

The final deliverable of The Log Farm project, was the BIM of the Bradley House. Out of all of the deliverables for the case study sites, this one proved to be the most challenging because of my limited knowledge of using Revit. Creating the model based off of the point cloud proved to be challenging because many of the building elements were warped and did not have simple geometries which are standard in Revit. Different element families were made to customize the elements as best as possible, but there were errors between the point cloud and the final model. As the model was being used for geometrical representation purposes, this result is acceptable. A stronger understanding of the software would have enabled for a more detailed model. This is something to research into for the future, especially in regards to developing my skill set in Revit, which needs improvement.

The final deliverables for Prince of Wales Fort were measured drawings for condition mapping, and a deformation analysis in CloudCompare detailing the current wall deformations. The images used in the photogrammetric process were able to produce orthophotos with a 5mm resolution, which is an acceptable result for the production of measured elevation drawings at a 1:50 scale, which illustrates the usefulness of using UAVs for fast and low cost image acquisition for the production of similar results. One application that I would have liked to implement was how the acquired images could be used in a crack monitoring program, which would have required orthophotos with a sub-millimeter resolution. This did not end up being the case, as even for the images taken at 3m away from the wall (those used in the deformation analysis), the resolution

was 1.2mm, still too high for a crack monitoring program. UAV photogrammetry proved to be advantageous at this site because the terrain could also be captured and properly aligned into the model. This helps to show the site in its surroundings environment, which is one of the character defining elements of the Prince of Wales Fort site. It can be concluded that UAVs are a very useful technique, as they can capture information in a fast and accurate manner. There are still constraints in regards to the camera capabilities. A camera with a larger sensor size opens up the possibility to the creation of higher quality results.

For QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen, the final deliverable was a digitally assisted condition mapping application for the KV62: Tomb of Tutankhamen. The way in which this virtual environment has been presented is as an unwrapping of the tomb surfaces for the purpose of condition assessment, not as a virtually immersive experience. It was designed for wall painting conservators to analyze each wall surface individually. This is especially useful for the ceiling areas, which are now brought into eye level. The main difficulty with this type of system is that there are limitations with virtual reality due to the inexperience of using game engines. The first is that there was difficulty creating a step ladder type of mechanism to teleport the user to a higher level of the wall painting surface. This is necessary because in the current state of the virtual reality environment, users are unable to see the tops of the painted surfaces from as close a view as those that are in the middle and at eye level. This is because of the height of the wall sections in the full scale virtual reality environment. This problem can be solved with more programming experience. Virtual Reality sickness is also a common problem, as sometimes the sense of immersion leaves the user feeling dizzy after wearing the headset for too long. The general conclusion that can be made about this outcome is that even though the resolution of the textures used in the virtual reality environment is quite high on a computer screen, they are not displayed

in the same resolution through the headset. This means that even though it was planned to be a conservation tool, the headset limits the immersion experience for condition mapping. Hopefully with technological evolutions in the future, this problem will be solved, and the resolution of the headsets will be comparable to seeing with the human eye. The application can still be used for viewing the painted surfaces in a full-scale environment.

Dissemination of the Documentation

The way in which the collected information could be disseminated was another important aspect of this research. For The Log Farm, the generated point clouds and BIM can be provided to the National Capital Commission for archival purposes, as they have started to digitize their collections. Unfortunately, due to the low level of detail in The Log Farm BIM, it was not suitable for presentation on the CDMICA website.

The focus was on using free open source software for analysis applications for the dissemination of the collected information for the Prince of Wales Fort case study. For the deformation analyses done with CloudCompare, they are easy to share with fellow practitioners. As long as the used point clouds are in an .e57 or .LAS file, then they can be accessed with this software for further analysis. The software is also user friendly and has a slow learning curve, enabling non-experts to compose these types of deformation analyses to be given to experts in the field to help with their decision making about the type of interventions required for the continued conservation of the Fort. An additional factor is that for digital heritage inventory purposes, a record of the flights is exportable from airdata.com in a .kml file, which was one of the types of inventories discussed in the literature review.

Finally, the dissemination aspect for this case study is a virtual reality model developed for the KV62: Tomb of Tutankhamen. The envisioned end product will provide an immersive

experience of being inside the Tomb without actually travelling to Egypt. It does not replace actually being at the site in person, but it is a way for people to become interested in the conservation initiatives that are currently being done by the Getty Conservation Institute. One possibility is for the Getty to establish a permanent virtual reality station at their museum with various immersion experiences of the different sites they have worked on to again provide information to the public in an interactive way.

Lessons Learnt

If the case study recording process was done over again, or if similar projects to those are conducted in the future, the following approaches and lessons learned should be considered in the documentation and deliverables workflow. They have been summarized into three main categories: recording, processing, and socio-cultural:

Recording

- Starting off the survey by taking natural control points that can easily be surveyed in the event that more time on site is required and that the targets must be taken down at the end of each working day.
- Taking more control points than necessary during the initial survey. This is because some may fall off over the course of a survey day.
- Remembering to take pinch-point scans during laser scanning (scans located in doorways/openings of two rooms or areas). This helps to ensure a large level of overlap between the respective scans, thereby aiding in their registration.
- The use of PhotoScan targets to cut down on processing time through the selection of markers in PhotoScan. This is recommended for sites that have many control points, as marking markers is a tedious, but necessary step.

- The use of spheres or surveyed targets to help align areas with low levels of overlap, such as combining interior and exterior areas.
- Automated image capturing applications should be used for UAV photogrammetry in order to save time while on site, especially in time-sensitive projects. These can always be supplemented with manual photographs, but because of the automated nature, it ensures that the specified overlap between images is met.
- For equipment, in UAV photogrammetry projects, three batteries and two chargers would be the optimal number. This would ensure that 60+ minutes of continuous flight time could occur, helping to speed up the data capturing process.
- Sufficient practice should be done while flying UAVs before image capturing on site in order to become more comfortable with the technique, just like with all the other recording strategies.

Processing

- When using Faro SCENE, it is good practice to unload clusters that are not being aligned during that specific stage.
- Saving after each iteration when using Faro SCENE because the software does not have an undo button. During each save, there is also a comments box where users can fill in what was done during that iteration if a file reversion is required later in the project workflow.
- Remembering to lock clusters when working in Faro SCENE after the scans have been aligned. This helps to ensure that individual scans will not be realigned in any further registrations.

- The importance of establishing a level of detail when using BIM and the use of a verification process to allow users of the model to understand the decision making process behind the work.
- For photogrammetric image processing with a large number of photographs, ContextCapture should be used to create the photogrammetric model because of the process of allotting a specific amount of RAM for the processing.
- If orthophotos need to be generated from a large data set in PhotoScan, then the processing methodology as seen in Appendix B can be used, which illustrated aligning the photos in PhotoScan and then exporting their parameters to ContextCapture where the mesh can be generated.

Socio-Cultural

- Establishing a rapport with local guides and site custodians is important to gaining a stronger understanding of the site, as they can provide information that cannot be seen by the data collected, such as past work done on-site.
- Interacting with the site on a more hands-on basis to complement the digital documentation strategies. This involves using the senses while analyzing the site, such as smell and tactile investigations.

Further Research/Deliverables

After analyzing the case study deliverables, some future research topics include:

The Log Farm

- Further research into BIM of historic timber elements;

- The development of geometrically-accurate building elements of the Bradley House BIM taken from the point cloud;
- Virtual Reality environment of The Log Farm that can be analogized back to the 1860's;
- UAV survey/video of The Log Farm site to provide aerial context to help aid in the Character Defining Element of preserving the experience at the site
- The use of a digital heritage inventory application for The Log Farm by using the Arches Project online framework as a way to disseminate information about the site to the public.

Prince of Wales Fort

- A comparison of commercially available low cost UAVs (those less than \$2000USD) containing built in cameras. A sample case study test can be conducted to compare and contrast the features of various models based on variables such as usability, battery life, and image quality.
- Testing of UAV image-capturing applications to compare the results of the photogrammetric models produced by each. Variables such as registration accuracy and point density can be used as variables for comparison.
- A Finite Element Modelling application of the walls of Prince of Wales Fort. Coring would need to be conducted to gain an understanding of internal wall composition;
- A Crack monitoring program through the use of UAV acquired images;
- Virtual reality environment of Prince of Wales Fort to aid in the dissemination of information to tourists in the Parks Canada Visitors Centre in Churchill, Manitoba;

QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen

- A serious game type of application for QV66: Tomb of Nefertari and KV62 Tomb of Tutankhamen

Chapter Summary

This chapter provided an overview of the developed workflows for the case study sites, as well as a discussion about the technical skill levels required for the case studies, and the project timeframes. It discussed the common parameters between the case study sites, such as the effectiveness of the data processing and dissemination outcomes, and the categories of learning outcomes that can be applied to similar documentation projects.

Chapter 11: Conclusions

From the development of optimized recording workflows, to the generation of useful deliverables for the heritage engineering community that can be easily disseminated, the four case study sites helped to illustrate how the problem statement of this research was solved and the knowledge base of each of the three main organizational principles (recording technique optimization, information interpretation, and information dissemination) was improved.

Choosing the correct technique at each of the case study sites, thereby influencing the quality of the data collected, helped to overcome the optimization of recording methodologies aspect. Products created from this collected data (including BIM, deformation analyses, and virtual reality) helped to contribute to an understanding of how these products can be used for conservation initiatives. The dissemination aspect of the problem statement was overcome by using free software and non-proprietary file types wherever possible (i.e. CloudCompare and Unreal Engine) as well as the interactivity nature of virtual reality for sharing of information.

The Log Farm case study helped to show the successful combined approach of using laser scanning and photogrammetry to collect information that contributes to posterity record keeping for the vernacular architecture in the Greenbelt. In regards to the final accuracy of the laser scanning point cloud, a final result of 6mm was acceptable. The next time scanning at the site occurs, the accuracy should be below 5mm. Building Information Modelling was also used to develop a simplified geometric model of the Bradley House to demonstrate how it can be used in heritage conservation projects. It is important to note that the limited skillset of the author was a governing factor in the final deliverable.

The Prince of Wales Fort case study helped to examine the role of UAVs in cultural heritage documentation, and their ability to capture information in a fast and accurate manner while

still producing high quality results. UAV recording workflows have been examined and lessons have been formulated about processes that can be incorporated into future missions, such as the use of automatic photograph capturing applications. The final resulting resolution of the generated orthophotos was 5mm, which was sufficient for the drawing of the individual stones. For further structural health monitoring applications, such as a crack monitoring program, sub millimeter resolution is required. Additionally, the registration errors of the model in PhotoScan can be improved from 9.4mm to a lower value if images are acquired at a closer distance, or with a camera with a larger sensor size.

The documentation of the QV66: Tomb of Nefertari and KV62: Tomb of Tutankhamen, answered research questions relating to software adaptations for heritage conservation projects, and the ability of information to be effectively disseminated. This case study also contributed to knowledge about conducting documentation projects on an international scale. The research questions were answered through the creation of a digitally assisted condition mapping application by using virtual reality technology. The game engine Unreal Engine 4 was used to accomplish this task, thereby showing how this software can be adapted for conservation purposes. For the dissemination of this information, the HTC Vive headset was used to allow users to become immersed in this virtual environment, showcasing a deliverable that is able to convey information about these historic tombs to the public.

Overall Research Findings

From this whole endeavor, a few final findings can be discussed, which apply to all four of the case studies:

Planning is Key:

This learning outcome relates to the fact that a documentation project cannot be done on a whim. Planning is required at each stage in the process, from developing an understanding of the site and its character defining elements, to the chosen technique used to capture the information. It all revolves around informed decision making that is achieved through planning. This concept of planning is also important in regards to checking over work once you leave the site—especially when working at sites that you cannot get back to easily (i.e. those you have to fly to). Planning is also important in regards to computer storage, as the complete set of documentation for the four case studies was approximately 1.5TB.

“To get the answer, you must know the answer”:⁴¹⁵

This quote, from Michael P. Collins of the University of Toronto, is known as the 3rd Principle of Engineering. This paradox underlines the basis upon which documentation projects are based. The scope of research dictates what the end products of any documentation initiative are, which thereby provides you with the answer before tackling the problem. The steps that are missing are how to best achieve this end result, which stems from the decision making processes involved with documentation. For example, in the Egypt documentation mission, the client wanted orthophotos with a resolution of 0.5mm. Therefore, in order to achieve this goal, photography planning was done in order to select the best camera for the job (in this case a full frame camera) and the distance at which photographs should be taken to achieve this final answer.

Take time to appreciate the site:

Even though the main goal of a documentation project is the collection of information, you never know when you will get back to that particular site, so take the time to experience it. This

⁴¹⁵ Luka Matutinovic, “The Only Engineering Rules You Will Ever Need,” July 9, 2015, <https://www.linkedin.com/pulse/only-engineering-rules-you-ever-need-luka>.

can involve going for an additional tour of the site, taking pictures, or speaking with the local site custodians or other tourists to hear their own experiences. This aspect was especially prevalent during the Egypt trip because of all of the rich heritage of the Valley of the Queens and Kings, and the fact that I did not know if I would ever get a chance to go back there in the future. It is also important to understand that documenting is more than just visual inspection. Even though hand recording techniques were not discussed in this work, they should be incorporated into the documentation process, as an additional tool to interpret the site.

Appendices

Appendix A: Log Farm Scan Information

Table A. 1: Log Farm Scan Information

Log Farm Scan Information				
File Name	Scan Information	Scan Profile	Scan Resolution	Scan Quality
Logfarm_Project_Scan_001	Central Scan focusing on Barn. Can also see the Bradley House	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_002	Focusing on Front-Right side of barn	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_003	Interior of Right side of barn	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_004	Right side of front of the barn, as well as right side view	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_005	right side view of barn exterior	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_006	right side of barn exterior, and part of barn exterior	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_007	rear of barn exterior (left side when looking at it)	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_008	rear of barn exterior	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_009	rear of barn exterior	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_010	rear of barn exterior	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_011	left side of barn exterior	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_012	left side of barn exterior	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_013	front of barn	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_014	front of barn	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_015	N/A	N/A	N/A	N/A
Logfarm_Project_Scan_016	interior of barn- middle	Indoor...10m	1/4	3x
Logfarm_Project_Scan_017	interior of barn- middle	Indoor...10m	1/4	3x
Logfarm_Project_Scan_018	interior of barn- middle	Indoor...10m	1/4	3x

Logfarm_Project_Scan_019	central scan on barn and house	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_020	central scan showing rear and left of house	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_021	central scan showing rear and right of house	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_022	scan showing front and right of house	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_023	scan showing front and left of house	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_024	scan showing front and left of house	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_025	scan showing front and left of house	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_026	scan showing rear and left of house	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_027	scan showing rear and right of house	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_028	scan showing front and right of house	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_029	scan showing front of house with targets to cellar	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_030	Scan in root cellar	Outdoor 20m...	1/4	3x
Logfarm_Project_Scan_031	Scan in root cellar	Indoor...10m	1/4	3x
Logfarm_Project_Scan_032	Scan in root cellar	Indoor...10m	1/4	3x
Logfarm_Project_Scan_033	Scan in root cellar	Indoor...10m	1/4	3x
Logfarm_Project_Scan_034	scan showing interior of house and exterior	Outdoor 20m...	1/4	4x
Logfarm_Project_Scan_035	scan showing kitchen of house	Indoor...10m	1/4	3x
Logfarm_Project_Scan_036	scan showing front of barn up to mezzanine. With spheres for registration	Outdoor...	1/4	3x
Logfarm_Project_Scan_037	in barn mezzanine level	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_038	in barn mezzanine level	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_039	in barn mezzanine level	Indoor...10m	1/4	3x
Logfarm_Project_Scan_040	first floor of barn- rear area	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_041	interior of barn- right side	Outdoor...20m	1/4	3x

Logfarm_Project_Scan_042	N/A	N/A	N/A	N/A
Logfarm_Project_Scan_043	interior of barn- right side	Outdoor...20m	1/4	3x
Logfarm_Project_Scan_044	interior of house-kitchen	Indoor...10m	1/4	3x
Logfarm_Project_Scan_045	interior of house-kitchen	Indoor...10m	1/4	3x
Logfarm_Project_Scan_046	hallway of first floor	Indoor...10m	1/4	3x
Logfarm_Project_Scan_047	back room in first floor	Indoor...10m	1/5	3x
Logfarm_Project_Scan_048	bottom of stairwell first floor	Indoor...10m	1/5	3x
Logfarm_Project_Scan_049	top of steps- first floor to second floor	Indoor...10m	1/5	3x
Logfarm_Project_Scan_050	second floor	Indoor...10m	1/5	3x
Logfarm_Project_Scan_051	second floor looking into two rooms	Indoor...10m	1/5	3x
Logfarm_Project_Scan_052	south room on second floor	Indoor...10m	1/5	3x
Logfarm_Project_Scan_053	north room on second floor	Indoor...10m	1/5	3x
Dec7_Scan_000	right side of front of barn	Outdoor 20m...	1/4	4x
Dec7_Scan_001	scan showing interior of right side of barn and exterior (tie in scan)	Outdoor 20m...	1/4	4x
Dec7_Scan_002	scan showing exterior and looking into house (door is open)	Outdoor 20m...	1/4	4x
Dec7_Scan_003	scan showing exterior and looking into house- closer than before (door is open)	Outdoor 20m...	1/4	4x
Dec7_Scan_004	scan showing exterior and looking into house- at bottom of steps (door is open)	Outdoor 20m...	1/4	4x
Dec7_Scan_005	scan looking into root cellar	Outdoor...20m	1/4	4x
Dec7_Scan_006	scan looking into root cellar but closer	Outdoor...20m	1/4	4x
Dec7_Scan_007	scan in entryway between root cellar and outside	Outdoor...20m	1/4	4x
Dec7_Scan_008	scan showing entry into root cellar	Outdoor...20m	1/5	4x
Dec7_Scan_009	exterior scan of house- front and right sides	Outdoor...20m	1/4	3x
Dec7_Scan_010	exterior scan showing right of house	Outdoor...20m	1/4	3x
Dec7_Scan_011	exterior scan showing rear and right of house	Outdoor...20m	1/4	3x

Dec7_Scan_012	exterior scan showing rear of house	N/A	N/A	N/A
Dec7_Scan_013	exterior scan showing rear and left of house	Outdoor 20m...	1/4	3x
Dec7_Scan_014	exterior scan showing left and front of house	Outdoor 20m...	1/4	3x
Dec7_Scan_015	exterior scan showing left of house	Outdoor 20m...	1/4	3x
Dec7_Scan_016	N/A	N/A	N/A	N/A
Dec7_Scan_017	N/A	N/A	N/A	N/A
Dec7_Scan_018	scan up to mezzanine with targets	Outdoor 20m...	1/4	4x
Dec7_Scan_019	N/A	N/A	N/A	N/A
Dec7_Scan_020	N/A	N/A	N/A	N/A
Dec7_Scan_021	scan in mezzanine with targets- looking down	Outdoor 20m...	1/4	4x

Appendix B: PhotoScan to ContextCapture Methodology

When exporting the parameters, a few steps had to be completed in PhotoScan to ensure that the values would be compatible with ContextCapture. The camera parameters cx , cy , $b1$, $b2$, and $k4$ were manually set to zero. Then, the cameras were re-optimized according to the settings in Figure B.2, and the resulting information was exported as an omega, phi, kappa text file from PhotoScan.

Figure B.1: Camera parameters to be changed
Screenshot of model from PhotoScan by author

Figure B.2 Camera parameters used in image alignment
Screenshot of model from PhotoScan by autho

The text file was then imported into ContextCapture. One important point to note is that in the Data properties window in ContextCapture, the camera orientation should be X right, Y up, in accordance with the coordinate orientation in PhotoScan, and the Spatial reference system set to ‘Non-georeferenced Cartesian coordinate system.’ This is shown in Figure B.3.

Figure B.3: Rotation parameter settings in ContextCapture
Screenshot of model in ContextCapture by author

The data from PhotoScan had to be was imputed in the correct order. Shown in Figure B.4, the column role should be changed in order to represent the information that is shown in that particular column in the txt file. For example, Column 1 represents the Photo Reference (photo name) so it is set to that value.

Figure B.4: Establishing Column roles in ContextCapture
Screenshot by author

Figure B.5: Camera parameters adjustment- parameters changed outlined in red
Screenshot by author

Some manual calculations were required in order to provide more accurate values for the new calibration of the images, specifically in relation to the Sensor size and Focal length. These are shown in the equations below:

$$\text{Sensor Size} = \text{pixel size(mm)} \times \text{image dimension width (pixels)} \text{ (Equation B.1)}$$

The pixel size is shown in Figure B.1, which is then multiplied by the image dimension width in pixels.

$$\text{Focal Length} = f \times \text{pixel size} \text{ (Equation B.2)}$$

For the focal length calculation, the f value and pixel size are both taken from Figure B.1 in order to complete the calculation.

After all of the parameters have been established, the aerotriangulation of the images were submitted. This process aligns the images based off of the precalibrated camera positions. When choosing the setting for positioning/georeferencing as seen in Figure B.6, the photo positioning for rigid data registration was selected because the photographs were to be registered based off of their metadata (camera parameters from PhotoScan).

Figure B.6: Positioning/georeferencing settings in ContextCapture
Screenshot by author

For the aerotriangulation settings as seen in Figure B.7, the important parameters are the position and rotation. These values had already been established by the metadata, and therefore were set to ‘Keep.’ The aspect ratio and skew were also kept to ensure that the images were not warped during the registration process. The other parameters were set to ‘adjust’ so the software could adjust them in the registration of the images.

Figure B.7: Aerotriangulation settings used to align the photographs in ContextCapture
Screenshot by author

After the aerotriangulation was completed and all of the images were aligned, the final step was the creation of a mesh. The format created was a ContextCapture 3MX file because after mesh tiles were completed, they could be visualized with ContextCapture. The texture compression was set to 100% to ensure the highest quality texture for the mesh (Figure B.8). After the 3MX mesh was created, the mesh was then exported as a Wavefront .obj file so it could be used in PhotoScan.

Format/Options
Choose output format and options for the production.

Format: **ContextCapture 3MX** 3D multiresolution mesh format, optimized for exchange with Bentley applications.

☐ Web ready

- ☐ Include proxy 3D model
- ☐ Generate Acute3D Web Viewer application

☒ Include texture maps

Texture compression: **100% quality JPEG**

Maximum texture size: 8192 pixel

☒ Level of detail (LOD)

Type: **Quadtree across tiles** is supported only for reconstructions using a tiling mode "Regular planar grid".

Type: Adaptive tree

Node size: medium (~35 kB/node)

☐ Skirt: 4 pixel

< Back **Next** Submit Cancel

Figure B.8: Mesh format and texture compression parameters used (highlighted in red)
Screenshot by author

Appendix C: Measured Drawing of Wall Section O-P of Prince of Wales Fort

Figure C.1: Measured drawing of wall section O-P

Areas within revision cloud were not drawn as they were not rectified in the photogrammetric processing, and as such, do not have the correct geometry.

Appendix D: Screenshots of Nefertari and Tutankhamen Drawing Set Layouts

Figure D.1: Sheet Layout for Chamber C in QV66: Tomb of Nefertari

Figure D.2: Sheet Layout for Side Chamber M in QV66: Tomb of Nefertari

Figure D.3: Sheet Layout for Burial Chamber Left Wall in KV62: Tomb of Tutankhamen

Figure D.4: Sheet Layout for Burial Chamber Sarcophagus in KV62: Tomb of Tutankhamen

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