

ANALYZING DIGITAL PHOTOGRAMMETRY FOR HERITAGE PRESERVATION

Robert Alan Kesack

Submitted in partial fulfillment of the requirements for the degree
Master of Science in Historic Preservation

Graduate School of Architecture, Planning and Preservation

Columbia University
May 2019

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Analyzing Digital Photogrammetry

for Heritage Preservation

Rob Kesack

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Author: Rob Kesack

Advisor: Norman R. Weiss, FAIC, FAPT, FSA

Readers: Carlos Bayod Lucini and David Flory, R.A.

Citation:

Kesack, Robert Alan.

“Analyzing Digital Photogrammetry for Heritage Preservation.” (Unpublished Master’s Thesis, Columbia University, Graduate School of Architecture, Planning and Preservation, 2019).

Cover Image:

Rob implementing photogrammetry on plaster ornamentation at La Casa de Pilatos in Seville, Spain, during the Fall of 2018, photo by Carlos Bayod Lucini.

Author Biography

Rob Kesack is a second-year graduate student in historic preservation at Columbia University’s Graduate School of Architecture, Planning, and Preservation. He holds a B.A. in Anthropology from Rhode Island College, in Providence. With his experience in computer science and technical photography, he recently worked with classmates at La Casa de Pilatos, a 15th century Andalusian palace, to evaluate a range of digital recording systems. Output generated from the project’s raw datasets was used to conceive a number of conservation and interpretation proposals for the site. His interest in digital heritage documentation stems from participation in two primary imaging workshops. He has also taken part in several preservation field schools across the country and abroad. Rob has served as an intern to both The Providence Preservation Society and The Garden Conservancy, and has organized a conservation field school at Woodlawn Cemetery, in New York City.

Abstract

Analyzing Digital Photogrammetry for Heritage Preservation is an in-depth analysis of the technical variables that impact photogrammetric processes utilized in architectural conservation. Precisely how do variables such as camera equipment, computer software, and hardware configurations alter the potential of digital photogrammetry, as a tool, for the building conservator? The core of this study focuses on the correlation between criteria such as accessibility, time, and cost concerning quality and practical, useful application. Given the rapidly evolving state of the digital world, often it is assumed that newer and more expensive technology equates to better results. Are we currently on the verge of the next technological leap in how heritage documentation is recorded and presented digitally? Does photogrammetry hold the key to facilitating this process? The project being presented addresses these questions through experimentation utilizing a range of camera equipment (from an iPad Pro to a Medium Format DSLR), experimental in-field and post-processing workflows, popular proprietary and open-source software. It takes an analytical approach to understanding the output obtained through experimentation. Although many in the conservation community are familiar with the concept of digital photogrammetry and are perhaps even experienced with the technique, there can often be a fundamental disconnect for individuals implementing the photogrammetry (and therefore choosing the equipment) and those with specific expectations for output on a given project. Lastly, this thesis presents findings in a way that can serve as a handbook for practitioners and clients alike when deciding on the most practical, cost-effective, and efficient approach for their needs.

Acknowledgements

First, I want to thank my loving parents, Bob and Celina Kesack. Without you, I would never have developed into the person I am today. You have made everything possible for me. It is because of you that I came to love both history and architecture.

A very big thank you to my advisor, Norman Weiss. You were truly the person who sparked my passion for pursuing preservation as a career. You are a great friend, mentor, and have been an extraordinary aid with this project all the way through.

I would also like to thank my readers: Carlos Bayod Lucini, the man who inspires my passion for always learning more about technology for preservation; and David Flory. David, I have such appreciation for your continued kindness and tremendous support.

Thank you also to those wonderful people who have given me excellent advice and spoken at length with me about my project, technology, and the fundamental concepts of preservation with me: Andrew Scott Dolkart, Will Reynolds, Stratos Stylianidis, Bilge Kose and, of course, Adam Lowe.

I also want to express my gratitude to the Historic House Trust of NYC, especially Executive Director John Krawchuck and Senior Architectural Conservator Derek Dandurand, for permitting access to the Dyckman Farmhouse.

On a deeply technological note, I want to thank Digital Transitions of New York City for their generous assistance in making their Phase One imaging equipment accessible for this project, and Bentley Systems for providing to me a complimentary research license to evaluate their software, ContextCapture.

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1 Heritage Documentation in the Digital Age

1.1 Significance of Heritage Documentation

Why We Document and the Role of the Digital Record

The desire to document our built heritage stems from an intrinsic human reverence for the objects which dominate and enhance our environment. Still photography changed the way people looked at and remembered buildings. Other developing technologies have enhanced the recording of significant features, measurements, and related defining characteristics of historic architecture. New forms of documentary media continue to emerge, even now, presenting new opportunities, ideas, and occasional challenges for the way we record material culture. The tools and processes of documentary preservation are continually evolving; there has been a no more exciting time for the field than now, in our current digital-centric age.¹

ICOMOS, the International Council on Monuments and Sites, is an organization that serves and supports UNESCO, particularly with regards to protecting and reviewing nominations for world heritage sites. ICOMOS is an organization with global reach and, as such, its standards for the documentation and recording of heritage sites are among the most comprehensive in the world. Because of this they are often applied to sites outside of their scope. As documentation is central to their overall mission, ICOMOS lists the following reasons for the usefulness of documenting cultural heritage:

¹ Robert E. Stipe, *A Richer Heritage: Historic Preservation in the Twenty-first Century* (Chapel Hill: University of North Carolina Press, 2007), 446.

THE REASONS FOR RECORDING (ICOMOS, 1996²)

from PRINCIPLES FOR THE RECORDING OF MONUMENTS, GROUPS OF BUILDINGS AND SITES (1996)

1. The recording of cultural heritage is essential:

- a) to acquire knowledge to advance the understanding of cultural heritage, its values and its evolution;
- b) to promote the interest and involvement of the people in the preservation of the heritage through the dissemination of recorded information;
- c) to permit informed management and control of construction works and all change to the cultural heritage;
- d) to ensure that the maintenance and conservation of the heritage is sensitive to its physical form, its materials, construction, and its historical and cultural significance.

2. Recording an appropriate level of detail to:

- a) provide information for the process of identification, understanding, interpretation, and presentation of the heritage, and to promote the involvement of the public;
- b) provide a permanent record of all monuments, groups of buildings and sites that are to be destroyed or altered in any way, or those at risk from natural events or human activities;
- c) provide information for administrators and planners at national, regional or local levels to make sensitive planning and development control policies and decisions;
- d) provide information to identify appropriate and sustainable use, and to plan useful research, management, maintenance programs, and construction works.

3. Recording of the cultural heritage should be seen as a priority, and should be undertaken especially:

- a) when compiling a national, regional, or local inventory;
- b) as a fully integrated part of research and conservation activity;
- c) before, during and after any works of repair, alteration, or other intervention, and revealing evidence of its history during such works;
- d) when contemplating total or partial demolition, destruction, abandonment or relocation, or where the heritage is at risk of damage from human or natural external forces;
- e) during or following accidental or unforeseen disturbance which damages the cultural heritage;
- f) when a change of use or responsibility for management or control occurs.

² "The Reasons for Recording," Principles for the recording of monuments, groups of buildings and sites (1996), ICOMOS, last modified January 11, 2012, <https://www.icomos.org/en/179-articles-en->

With an enormous number of historic properties now being captured digitally, a new level of precision and accessibility has become possible. Documenting through digital means not only allows for recording and visualizing data with similar methods to traditional two-dimensional techniques such as line drawings, but additionally presents seemingly countless new ways to produce and present this information. Today's digital documentation services many needs; this type of documentation yields highly precise data, including exceptionally detailed information about dimensions, conditions, and textural appearance. The digital representation is a near-exact replication of the actual building or object captured, and not a stylized approximation, as seen in hand-drawn versions and AutoCAD blocks.

Captured digital documents may serve as the only detailed record should a historic property or object be damaged or lost entirely. Now more than ever, due to factors like sharing information through multiple accessible platforms, more advanced and affordable equipment, and the engineering of new software, digital documentation is a comprehensive and invaluable conservation resource. Not only can digital documentation provide an enhanced understanding of the object or site studied, but it acts as a cross-disciplinary tool, enabling data integration and manipulation between architectural professionals without the need for proprietary software or equipment.

For example, 3D digital records not only identify materials and map conditions of a building, but they can be used to monitor minute physical changes in the structure over time. Importantly, digital media represent the potential for non-invasive interventions, such as digital restoration, something relevant to the preservation field and the ethos of "no harm done." Digital data often function as a form of stewardship, virtually archiving the characteristics of the built environment and helping to educate further and engage an increasingly connected global population.

1.2 Applications for Digital Documentation

What Can You Do with Your Data?

One of the many questions that seem to arise when one is introduced to the idea of recording heritage digitally is “What exactly can I do with all of this wonderful information?” The short answer is almost anything. From interpretation and analysis to monitoring and even replicating, the applications for digital documentation seem only to be limited by imagination and creativity.

For example, engineers and conservators utilize data recorded with traditional tools and incorporate this information into drawings, photographs, and even physical models. Stress fractures, cracks, displacement, stains, and loss are all prime examples of the types of information that practitioners could instead expect to share and analyze digitally. Many preservationists and architects use digital information to reconstruct something lost to history or to propose new interventions. Artists can use digital data to replicate an original object or implement an imaginative take on something historical in a non-invasive way. Site managers and owners can use digital documentation to raise funds, which in turn will serve the overall sustainability of their site or property. The table below lists several practical functions of 3D digital documentation.

Objective/Scientific Documentation	Subjective/Curatorial Documentation
<ul style="list-style-type: none"> • Accurate 3D Models • Measured Drawings • Tracking Material Changes • Comparative Analysis • Screen-Based Imaging of Multi-Layered Data • Reverse Engineering • Archaeological Survey • 3D Fly-Throughs 	<ul style="list-style-type: none"> • Re-materialization and Facsimiles • Digital Restorations • Reinterpretations • Prototyping Mounts • Advocacy and Fundraising

1.3 Forms of Output

What Shape Will Your End-Product Take?

One of the most exciting and sometimes daunting aspects of recording and utilizing digital data is considering what output is appropriate for your needs, and for the needs of a client or other stakeholders. Thanks to the flexibility of today's computers and the software developed to manipulate digital data, there is a myriad of possibilities for the type of output one can develop at the end of a given project.

Within the contemporary architectural spectrum, generation of several significant products is possible. Many of them can be composed clearly and with speed. One of the most heavily relied-upon visualizations in this field is the measured drawing. Measured drawings are two-dimensional. It is easy to create the line work for these drawings from something as simple as the raw point cloud or orthographic images extrapolated from digital models. Of course, the point cloud and orthographic images can themselves be used as visualizations, as they are often able to provide levels of detail and context that still photographs cannot. Orthographic images can also act as a base layer for the generation of site maps or for mapping out and documenting things like material conditions.³

Point Cloud

"Point clouds are dense groups of 3D data points that digitally replicate your project for design and construction. It's a visualization of reality in which every point represents a [piece] of your building or project."⁴

In a museum setting, digital data can be manipulated to produce useful physical and virtual forms for an exhibition. Possibilities of visualization include physical models, videos and video-mapping, reconstructions, and so on. These types of displays can reach

³ Further information on measured drawings regarding their significance, purpose, and creation, can be found in the book *"Recording Historic Buildings"* compiled by HABS and found in PDF form here: <https://www.nps.gov/hdp/habs/RecordingHistoricBuildings.pdf>.

⁴ "Point Cloud," *Epic Scan*, accessed March 10, 2019, <https://epicscan.com/tag/point-cloud>.

a broader audience that the original object or building could not. When carefully collected, all of this data can be classified and interpreted for use in marketing and advocacy which has the potential to generate frequently needed public interest. In turn, this facilitates populating access to customarily restricted data between institutions which allows global scholarly collaboration. Other virtual outputs are furthering accessibility, by breaking down the barriers which limit the ease of access to the original; these include fly-through animations, time-lapse reconstruction, virtual reality tours, and textured 3D models, and so on.

Digital Output	Physical Output
With digital output, everything that happens is screen-based and experienced through a computer.	Physical outputs yield any product through which re-materialization is possible (e.g. prototyping, replication, and so on)

1.4 The Ethics of Recording & Copyright

Value of the Reproduction

With the launch of every new documentation-oriented technology, there always seems to be two factions: those who support the latest advancements, and those who are uncertain of their advantages and are thus cautious to adopt them. Some 150 years ago, during the height of the Industrial Age, Sir Henry Cole sided with the attitudes of the former. Cole advocated embracing modern technologies. His argument was specific to the influence of technology on the preservation of culturally significant objects. Cole addressed his opinions on the importance of technology in his 1867 Convention for Promoting Universally Reproductions of Works of Art for the Benefit of Museums of all Countries.

In the Convention, Cole firmly states that reproductions of culturally significant objects hold a value all their own. He believed in the power of the knowledge that reproductions could instill in the casual observer, as well as the academic. To Cole, technology (mainly plaster casts, electrotypes, photographs, and other emerging methods of the era) represented an opportunity to understand and access that which was otherwise distant and inaccessible; his argument parallels the perceived significance placed on technology and reproductions (physical and virtual alike) today.⁵

⁵ "1867 Convention," *Reading Design*, accessed March 10, 2019, <https://www.readingdesign.org/1867-convention>.

Who Owns the Rights to Your Documentation?

The pervasiveness of digital documentation techniques in today's society has made recording significant heritage items more easily achievable. Now, items around the world are recorded by today's "public curators", as everyone, with the advances of mobile cellular technology, seems to have a camera in his or her pocket. This inundation of media to the collective cultural archive yields some questions and challenges, most especially, who own the rights to the recorded images and videos of the objects?

Currently, there are no hard and fast regulations governing the capture and use of images taken of historical objects. The public discussion has gone on for some time, yet there exists no materialization of any specific laws. Launched by UNESCO in May of 2017, the ReACH (Reproduction of Art and Cultural Heritage) Declaration was the first significant response to emerging technology and reproductions since the 1867 Convention of Henry Cole. ReACH, in part, strives to address issues of the creation of digital data such as production and storage, yet remains silent on the topic of copyright.⁶ As of now, copyright of digital documentation, specific to heritage preservation, is addressed on a case-by-case basis by those parties involved in the recording process. Who retains rights to the information is unclear. Often, ownership of material is either given to the party doing the recording, or to the client who owns the property. The basis for this is a fundamental principle of "whoever pays for it, owns" it unless stipulated otherwise (e.g., when organizations like CyARK offer their services pro-bono, or when ownership is explicitly written in a contract).

⁶ Anaïs Aguerre "ReACH Declaration" (PowerPoint presentation, 2019 Fitch Colloquium, New York, NY, February 15, 2019).

1.5 Authenticity (Objectivity vs. Subjectivity)

Concept of Authenticity

The concept of authenticity is something that can have a different meaning to different individuals. Authenticity is often the subject of considerable argument in conservation and, yet many times, is the guiding principle for how a project is carried out. It is a subjective term, as applied to digital documentation, where often, we as professionals cannot be entirely sure to what degree of faithfulness our digital recordings represent to the original object in question, and whether the outsider understands this limitation.

On January 24, 2000, a group known as the Council on Library and Information Resources (CLIR) assembled to address this issue in the digital context. CLIR stated that “Authenticity’ in recorded information connotes precise, yet disparate things in different contexts and communities. It can mean being original but also being faithful to an original; it can mean uncorrupted but also of clear and known provenance, ‘corrupt’ or not.”⁷

Architectural documentation is itself a representation. Any attempt to interpret the physical elements of built heritage is inherently biased by varying degrees of subjectivity. A certain unavoidable level of corruption occurs to information as it is manipulated into a final interpretation. Photogrammetry and any other contemporary digital recording techniques mitigate, to some extent, these effects of informational corruption. These methods are currently the best means available for recording built heritage, despite their drawbacks. Such biases can affect the sense of authenticity, which specifically in this case refers to the degree by which an interpretation conforms to the core qualities of the original.

⁷ Charles T. Cullen et al., *Authenticity in a Digital Environment* (Washington D.C.: Council on Library and Information Resources, 2000), vi, <http://www.clir.org/wp-content/uploads/sites/11/pub92.pdf>.

Impacts on Authenticity in Digital Recordings

Multiple factors can have an impact on digitally recorded information. One of these factors is “optical bias”. Optical bias refers chiefly to two main dynamics: context, and lighting. Context is how still photographs are framed and captured. This type of bias can be either intentional or unintentional. When photographing, it is often the case that the photographer attempts to frame the subject in the best orientation possible. Consequently, this means that sometimes absent from the recorded image are the surrounding areas and other pertinent background information. Such a result may be the intended effect of the photographer or an unintentional oversight when on a photographic shoot.⁸

Environmental lighting is a matter that extends beyond the issue of contextual surroundings when recording digital images. Not only does lighting influence project planning (e.g., the most opportune time to photograph an object) and the ability to record clear, sharp, and detailed images, it ultimately affects the interpretation of an image. Lighting conditions have a very distinct effect on objects and buildings. How one understands an object differs when light deviates from the original setting and environment. One particular example of this is the archival collection of photographs of “The Blond Boy” (the head to an ancient Greek Kouros removed from the Acropolis) taken by photographer and archaeologist Ernst Langlotz in the early twentieth century.

The issue with Langlotz’s photographs is a subject that was highlighted by David Gissen, Professor & Associate Chair of Architecture at The California College of the Arts, in his recent talk at the 2019 Fitch Colloquium in New York City. Gissen contends that Langlotz was keenly aware of the effect of lighting on interpretation. He specifically applies the observations of Langlotz to the digital record and has found a method to alter and control the lighting of an environment digitally, and hence, to modify the lighting of an object. Gissen suggests using a post-production software application known as

⁸ Brigid Boyle, “Full Stop?: An Investigation into the Significance of the Period of Significance,” Frank Lloyd Wright Quarterly 27, no. 1 (January 01, 2016): 22-27.

Radiance to simulate and manipulate exact and alternate lighting to affect the public's perception and understanding.⁹

Optical bias is but one of many factors by which the digital record can be influenced and therefore its authenticity challenged. Adam Lowe, Director of Factum Arte, a Madrid-based firm which blurs the lines between art, preservation, and replication through the use of new and emerging technologies, has reflected on several occasions about the bias introduced to the digital record not only through the capturing of the data but through the stages of data processing and output as well. Lowe is a firm believer that the introduction of subjectivity to digital preservation work is found at every step of the process. He suggests that every variable along the way impacts, in one manner or another, the digital record and causes unique deviations, sometimes imperceptible, from the original object.¹⁰

Lowe explains that we see this influence from the equipment used to record, to the software used for processing the data, to the automatic, manual or computer algorithmic-driven methods of stitching images, and in the way that a digital documentation specialist manipulates the data to address such issues.¹¹ Further to this point regarding the influence of the digital recording and post-processing workflow, another variable which inhibits or alters the authenticity of a digital object is the presence of "digital lacunae." Digital lacunae are as the name implies, holes within the digital record. Introduction of these holes could happen at nearly any point in the recording stages; five distinct categories of these holes are: embedded, experiential, usage, enacted, and strategic and are explained in the table below.¹²

9 David Gissen, PhD, "The Environmental Reproduction of Cultural Artifacts" (PowerPoint presentation, 2019 Fitch Colloquium, New York, NY, February 15, 2019).

10 Adam Lowe, "Data reality," *Future Anterior: Journal of Historic Preservation, History, Theory, and Criticism* 12, no. 2 (Winter 2015): 4-5.

11 Ibid.

12 Andre Paul Jauregui, "Heritage Reproduction in the Age of High-Resolution Scanning: A Critical Evaluation of Digital Infilling Methods for Historic Preservation" (thesis, Graduate School of Architecture, Planning, and Preservation, Columbia University, New York City, 2018), 14.

Types of Holes

from HERITAGE REPRODUCTION IN THE AGE OF HIGH-RESOLUTION SCANNING: A CRITICAL EVALUATION OF DIGITAL INFILLING METHODS FOR HISTORIC PRESERVATION (2018)¹³

Embedded Holes

Embedded holes are part of the physical object, and they exist before the scanning has taken place. An example would be scanning a painting with a tear in it. The damage is an embedded attribute of the object.

Experiential Holes

Experiential holes are missing attributes of an object that contains human perception including the human sensorial perception that can assist in subjective metaphysical interpretations. An example of this would be a model of an Italian castle that does not include elements of the Tuscan landscape behind it or local people.

Usage Holes

Missing information about the pattern of organization of the critical actions that take place around the object, and the processes of interacting with it, its environment, and data from its environmental attributes. An analogy would be a model of the Egyptian Pyramids without the city of Giza shown.

Enacted Holes

Enacted holes occur during the reconstruction process and are externalities of scanning processes or due to operator error. An example of an enacted hole is a church model derived from a scan that is missing the roof because the technician was unable to scan a tall structure. Or a hole occurring due to a reflective surface that a scanner was unable to record.

Strategic Holes

Strategic holes are holes that occur in models for the purpose of external needs or deception. An example of a censured hole is the strategic prioritization of a portion of an object over another due to time/site constraints. Another would be the removal of a confederate flag from a scanned confederate monument.

13 Andre Paul Jauregui, "Heritage Reproduction in the Age of High-Resolution Scanning, 14.

1.6 Data Management

Digital Archives & Catastrophic Data Loss

With the exponential adoption of and access to digital recording techniques and tools, one challenge that arises is the stable storage of the digital data itself. The loss of digital data is a legitimate concern. All too frequently, the hard drives which house digital archives fail, and data is sometimes lost forever. Data loss does not exclusively happen through mechanical error; many times, human factors play a role in loss of valuable digital information. It's a commonplace event for those handling the data to make simple errors and accidentally delete or write-over their archives. Extreme environmental events also can profoundly impact the security of stored digital data. For example, Hurricane Katrina and 9-11 were both catastrophic events associated with data loss on a large scale.¹⁴

While data loss through equipment failure and catastrophic events seems rare, this situation is certainly a reality. There must be consideration for exactly how data are safeguarded; preventative measures should be in place. Consideration for where information is stored and archived, such as in a vault or fireproof room, away from the impacts of natural disasters, is a first step to safeguarding a digital archive. Other methods to protect data rely on the methods for archiving of the data itself. Data should always be backed up frequently and in multiple locations. This form of redundancy is known as "mirroring" and is one of the best ways to ensure that data remains accessible, even in the worst scenarios. Relying on the recovery or digital reclamation of your data after an event is ineffective, unpredictable and yet often easily avoidable with proper archival procedures and practices.¹⁵

Catastrophic loss is not exclusive to digital records. It is simply how we plan for

14 William C. Dougherty, "Preservation of Digital Assets: One Approach," *The Journal of Academic Librarianship* 35, no. 6 (November 2009): 1, <https://www.sciencedirect.com/science/article/pii/S0099133309001505>.

15 Ibid.

and mitigate the loss that differs from the methods we practice to protect other forms of documentation. Nothing is indestructible. Books, artifacts, drawings, prints, tintypes, and so on are all equally prone to destruction in a cataclysmic scenario. Each artifact and record is susceptible to its specific forms of loss and degradation. Indeed, there is an argument to be made that traditional forms of documentation are more fragile than their digital counterparts.

File Formats & The Continuing Obsolescence Dialog

Obsolescence of certain aging file types is an ongoing issue with particular relevance to the field of digital heritage documentation. Many people worry whether or not file formats created some decades ago, particularly those which are proprietary and associated with specific standard 3D digital programs, can stand the test of time. The Library of Congress itself, one of the Nation's largest repositories of historic architectural documents, is one such entity that shares in an apprehension for future compatibility and access to files created using currently favored formats. Instead, they prefer to accept only analog forms of documentation. Mostly, however, at least to this point, there has been only limited genuine concern with these file formats. With the advent of virtual machines and continually emerging open-source software, this problem is only likely to be diminishing. The existing common and often standard formats used by today's most popular programs are essentially universal, and several programs can usually open them. Where one proprietary file format exists for a given program, many times an open-source program is able to load that file type.

As of 2019, there are many shared and common file formats that pertain to the realm of digital documentation. The formats that relate specifically to the 3D models being generated on today's equipment are as follows:

Common 3D Model File Formats:

OBJ (ASCII)
OBJ (Binary)
FBX
Collada
3DS
IGES
STEP
PLY

2 Introduction to Photogrammetry

2.1 Architectural Photogrammetry

What is Photogrammetry?

Photogrammetry is a distinct and useful tool with many applications in the field of architecture. Fundamentally, photogrammetry is a scientific method. It is a hybrid photographic technique which relies on the general principles of photography (using still photographs), combining them with the mathematical rules of geometry to provide precise measurements of a building, and make possible a 3D reconstruction. The capture of a single photograph or a composite of two or more images makes this type of reconstruction possible.¹

The development of photogrammetry unfolded over many decades, since its conception in the mid-nineteenth century. An embracing of the technology as a practical tool for historic structures came later, following many experiments and the backing of several influential organizations. The technology developed some serious traction as a tool for architectural cultural heritage measurements in the 1960s. Internationally, The International Council on Monuments and Sites (ICOMOS) and their subsidiary the International Committee for Documentation of Cultural Heritage (CIPA) began to embrace and advocate photogrammetry as a promising alternative to the conventional methods of recording.²

The Historic American Buildings Survey (HABS), the foremost authority on

1 Harley J. McKee, *Recording Historic Buildings* (Washington D.C.: U.S. Department of the Interior, National Park Service, 1970), 41-42.

2 Nurul Hamiruddin Salleh, "Architectural Photogrammetry for the recording of Heritage Buildings: An Overview," *Journal of Architecture, Planning & Construction Management*, 2, no. 2 (2012): 2, <https://pdfs.semanticscholar.org/dbc7/e18360d0c574d46f64e4e8b028deabed2612.pdf>.

and producer of historic architectural documentation in the United States, cited photogrammetry as early as 1970, as an acceptable tool for the recording of architectural measurements. Still relatively unavailable at that time, photogrammetry was a tool best reserved for instances where high precision was necessary, and where hand-measuring methods proved to be overly complicated. Before advancements in the digital age, and its existence within the digital context which we are most familiar with today, architectural photogrammetry was a highly specialized field which required unusual equipment and skill sets. Before the wide use of computers and efficient digital equipment, photogrammetry was utilized sparingly, not only due to its reliance on experts and specialized equipment, but because of the cost and time associated with the technique.³

Advantages of Photogrammetry

As in its early days, some specialized skills remain associated with the photogrammetric recording and documentation process; such specialization is becoming less of a barrier, however, with breakthroughs in modern technology, making accessibility of the tool far more widespread than ever before. The primary advantages of photogrammetry remain constant, only further enhanced by means of the perpetual and exponentially evolving digital landscape. Potentially, many applications for the technology are not yet fully realized.

³ Harley J. McKee, *Recording Historic Buildings*, 41-42.

Current Key Advantages of Photogrammetry⁴
<p>1. Efficiency through the photographic capturing method.</p> <ul style="list-style-type: none">• The need for equipment such as scaffolding is not necessary to achieve quality recordings.• Specialized equipment is less necessary. (Even cell-phone cameras can be used to record images)
<p>2. Precision of Data and Measurements.</p> <ul style="list-style-type: none">• There is superior accuracy in the precision and uniformity of geometric calculations, computer processing, and resulting structural measurements.
<p>3. Survey Savings (Time and Money).</p> <ul style="list-style-type: none">• Complex objects such as those that are curved or otherwise irregular are easily measured and are better able to be analyzed and assessed.
<p>4. Measurement of Fragile/Difficult-to-Access Objects.</p> <ul style="list-style-type: none">• Photogrammetry is a very hands-off, non-invasive recording method.• Use of X-ray, FLIR, and other such methods which record otherwise invisible spectrums allow the recording of invisible features.
<p>5. Safety.</p> <ul style="list-style-type: none">• Surveying of impossible or even dangerous to reach places is possible through photogrammetric recording.
<p>6. Analytical Observations of Distortion/Deformation.</p> <ul style="list-style-type: none">• 3D modeling reveals distortions in buildings not noticed or appreciated by the human eye.
<p>7. Retention of Digital Data.</p> <ul style="list-style-type: none">• Digital archiving of data recording with photogrammetry can be stored and accessed at a later date. (Making possible the future ability to revisit data and approach with new methods and technology)

8. Comparative Observation and Monitoring.

- Take raw (uncompressed) photographs at various time intervals (short or long-term).
- This approach can allow for a before/after comparison of the rate of deterioration for building/object materials.

Beyond the advantages to the process, output types and other applications for this tool within historic preservation and architecture are invaluable. Photogrammetry is not limited to capturing the exterior of a structure; it can also record interiors. Moreover, it can do this in a more efficient and versatile way than some other methods. Should a building be damaged or lost, reclaiming these essential architectural elements is possible through replication; the whole structure, too, can be restored or reconstructed, if that approach is selected. The first instance of this, where an entire structure relied on the data from a photogrammetric recording, was in England at Castle Howard (Figure 1-1) in the 1960s.⁵



Figure 1-1. Castle Howard, south front (1904)

4 Bernard M. Feilden, *Conservation of Historic Buildings*, 3rd ed. (New York, NY: Architectural Press, 2003), 223.

Table modified here to reflect current dispositions and uses.

5 Bernard M. Feilden, *Conservation of Historic Buildings*, 223.



Figure 1-2. Castle Howard, south front after fire of 1940.

Historic photographs were used to determine measurements of the building after a devastating fire the 9th of November, 1940. The fire destroyed the dome, portions of its lantern, part of the octagonal drum to the level of the frieze, along with eight classical busts. Additionally, lost to the fire were the rooms of the east wing and the central block south of the dome (Figure 1-2). This restoration process relied heavily on a collection of about 140 historical photographs, taken over the course of a century. In the cases where photographs weren't available, "artificial photographs" could be simulated through the use of a known coordinate system applied to both the building and the pre-fire photos, in conjunction with the principles of geometry.

Invention of Photogrammetry



Figure 1-3. Albrecht Meydenbauer

Not long after Nicéphore Niépce used a camera to capture the first photographic image in 1826 or 1827, people began to realize the potential of the power of the camera.⁶ Albrecht Meydenbauer (Figure 1-3), a German architect, working, just a few short decades later, recognized that photography, and the information it contained within it, could be of enormous value to the field of architecture.⁷ Later, he applied photogrammetry on a larger scale for topographical mapping to various civil engineering and military projects.⁸ Meydenbauer, apparently

the individual who coined the term photogrammetry, composed a memorandum, in which he wrote in length about the importance of the information stored within a photograph. In the memorandum, Meydenbauer elaborated on how images had the power of capturing highly accurate details about the objects which they recorded.⁹

In 1867, after a series of optical equipment designs and experiments conducted by Meydenbauer (begun in 1858), the first instrument built specifically for photogrammetry was produced by the workshop of Emil Busch, located just outside Berlin. Meydenbauer was able to perform a series of significant tests with this instrument. His objective was

6 Robert Hirsch, *Seizing the Light: A Social History of Photography* (New York: McGraw-Hill Higher Education, 2009), 8. Ibid.

7 Joerg Albertz, "A LOOK BACK. 140 Years of 'Photogrammetry'. Some Remarks on the History of Photogrammetry," *Photogrammetric Engineering & Remote Sensing* 73, no. 5 (May 2007): 504, <https://www.asprs.org/wp-content/uploads/pers/2007journal/may/lookback.pdf>.

8 Albrecht Grimm, "The Origin of the Term Photogrammetry - Isprs.org," *History*, accessed May 5, 2019, <https://www.isprs.org/society/history/Grimm-The-Origin-of-the-Term-Photogrammetry.pdf>.

9 Joerg Albertz, "A LOOK BACK. 140 Years of 'Photogrammetry', 504.

a measurement study focusing on recording not only architecture but also documenting topological terrain data. This study, and those conducted for many years after, mainly proved promising.¹⁰

Meydenbauer's strategy relied on the enlargement of a single photograph and the georeferenced calculations of an un-rectified photograph (those showing perspective-related distortion). This approach, referred to as mono-photogrammetry, depends on the use of only one photograph.¹¹ Mono-photogrammetry is also often referred to as mono-plotting.¹²

Metric and Conventional Cameras

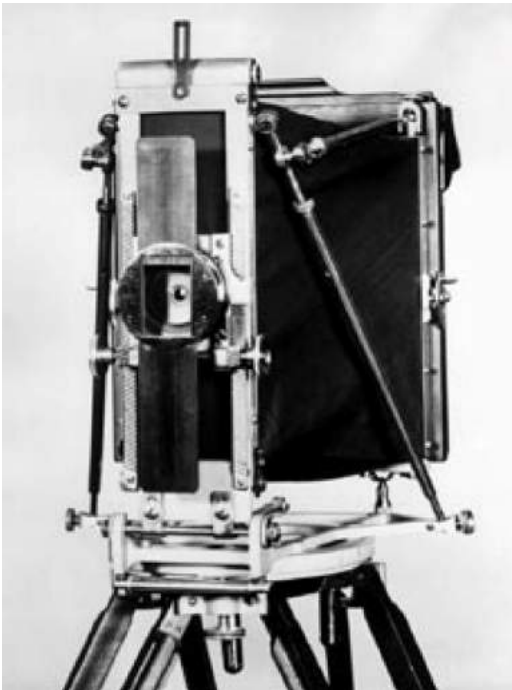


Figure 2-4. Metric camera designed by Meydenbauer (1890).



Figure 2-5. Metric camera produced by DJI for mounting on aerial drone.

Many of Meydenbauer's experiments (and the work done by his contemporaries) relied on cameras known as metric cameras (Figures 2-4 & 2-5). Additional precision is

¹⁰ Ibid, 504-505.

¹¹ C. Bozzini, M. Conedera, and P. Krebs, "A New Monoplotting Tool to Extract Georeferenced Vector Data and Orthorectified Raster Data from Oblique Non-Metric Photographs," *International Journal of Heritage in the Digital Era* 1, no. 3 (2012): 501, doi:10.1260/2047-4970.1.3.499.

¹² Ibid, 502.

part of metric camera's design. Metric cameras have a known inner orientation as well as a calibrated radial distortion. Photographs taken with these cameras require no additional correction when being used for plotting or architectural restitution.¹³ The tables on the following page present a comparison of the advantages and disadvantages of metric and conventional cameras.

Metric Cameras²	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Value of the principal distance is accurately known • High resolving power (greater detail) due to lenses with minimal distortion • Minimal deformation of film 	<ul style="list-style-type: none"> • Expensive • Require special knowledge to operate
Conventional Cameras³	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Greater accessibility • Motor-driven • Can be hand held • Lower cost 	<ul style="list-style-type: none"> • Unstable geometry • Lenses often have greater distortion • Cost of lenses depends on quality desired (i.e. less distortion and higher resolving power) • Small image size

Acceptance of Photogrammetry

With Meydenbauer's accomplishment, the architectural community acknowledged photogrammetry as a useful tool for obtaining architectural measurements, and he was appointed, by the Prussian Minister of Culture, as the director of the Royal Prussian Photogrammetric Institute, which he co-founded.¹⁴ Mono-photogrammetry can still be

¹³ Otto R. Kölbl, "Metric or Non-Metric Cameras," *Photogrammetric Engineering & Remote Sensing* (January 1976): 105-106, https://www.asprs.org/wp-content/uploads/pers/1976journal/jan/1976_jan_103-113.pdf.

¹⁴ Joerg Albertz, "A LOOK BACK. 140 Years of 'Photogrammetry', 504.

useful, although through its development and application, there was a gradual awareness that two images or stereo pairs (sometimes called stereo photograms) afforded much more information. Today, we generally think of photogrammetry as a much more robust process which sometimes relies on not just a composite of two, but thousands of images to create remarkably detailed models and to provide us with far more than just accurate measurements.

Camera Lucida

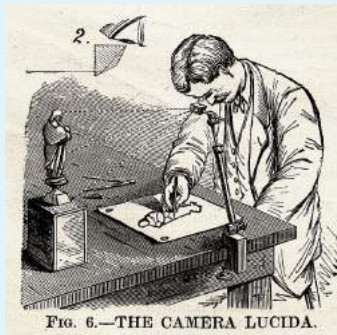


Figure 2-6. Camera Lucida in use

“An instrument in which rays of light are reflected by a prism to produce on a sheet of paper an image, from which a drawing can be made.”¹⁵ (Figure 2-6)

Meydenbauer was not the only one to work on the technology behind photogrammetry during its early stages. Beginning in 1849, Aimé Laussedat, a French military officer, started prototyping equipment to draw the façade of the Hotel des Invalides. Later, he used a similar method to produce topographic maps. Despite having relied on a tool known as a Camera Lucida, in place of a more conventional camera, Laussedat is commonly considered as the pioneer of the field, the grandfather of photogrammetry.¹⁶

¹⁵ “Camera Lucida,” Items, Museums in Israel: National Portal, date accessed May 5, 2019, <https://museums.gov.il/en/items/Pages/ItemCard.aspx?IdItem=ICMS-MTC-3295>

¹⁶ Karl Kraus, Ian Harley, and Stephen Kyle, *Photogrammetry: Geometry from Images and Laser Scans* (Berlin: De Gruyter, 2007), 3.

Obtaining Measurements through Rectified Photography

Before and concurrent with the advance of photogrammetry for architectural applications, other methods (e.g., traditional hand measuring, geometric triangulation, and so on) were developed to aid in the determination of reliably precise measurements. One of those methods was simply the direct derivation of measurements from photographs. Meydenbauer can be considered at the forefront of this critical photographic development as well. After designing the first successful wide-angle camera system for photogrammetry, he continued the development of new and improved equipment. One of the significant evolutions of his design was a camera with a lens which could shift its internal optics vertically to obtain a rectified image (Figure 2-7), one devoid of distortions caused by perspective (see Figure 2-2, p.22).¹⁷



Figure 2-7. Example of a rectified image captured by Meydenbauer, French Cathedral in Berlin (1882).

Achieving this type of rectified image before camera lenses were able to correct perspective-related distortion required altering the image itself as part of a post-

¹⁷ Joerg Albertz, "A LOOK BACK. 140 Years of 'Photogrammetry'", 505.

development process (referred to as rectifying the negative). Rectifying the negative was a challenging and a laborious process which took a great deal of time. Rectifying the negative, a process completed entirely in a darkroom setting, is done in several ways. The most common of those ways is to either physically tilt a print easel as a negative is being processed into a positive proof (a chemically manifested reversal of the negative to paper known as a print) and then enlarge the image or to use what is known as a rectifying enlarger which is purpose-built for this task. After achieving rectification of the negative, the image can be scaled up to any workable size necessary. Either method results in an enlargement where measurements can be recorded and suitably scaled.¹⁸

Up through the early 1960s, rectified photography in and of itself was an extremely specialized practice, generally limited to specialized large format cameras (aka “view cameras”, similar to what Meydenbauer had designed). These were heavy, difficult to carry, and required special photographic skills to operate, and therefore were not particularly practical. In 1962, however, a milestone in new portable small format cameras and innovative lens design introduced the world to the first perspective correcting lens (35mm f3.5 PC-Nikkor) meant for a more portable camera system, the Nikon F (Figures 2-8, 2-9, & 2-10).¹⁹



Figure 2-8. 35mm f/3.5 PC-Nikkor (1962)



Figure 2-9. Nikon F camera with mounted PC-Nikkor lens.

¹⁸ John A. Burns, *Recording Historic Structures: Historic American Buildings Survey* (Washington D.C.: American Institute of Architects Press, 1989), 132.

¹⁹ “Nikon PC-Nikkor 35mm f/3.5,” PC_Nikkor, MIR, http://www.mir.com.my/rb/photography/companies/nikon/nikkoresources/PC_Nikkor/index1.htm.

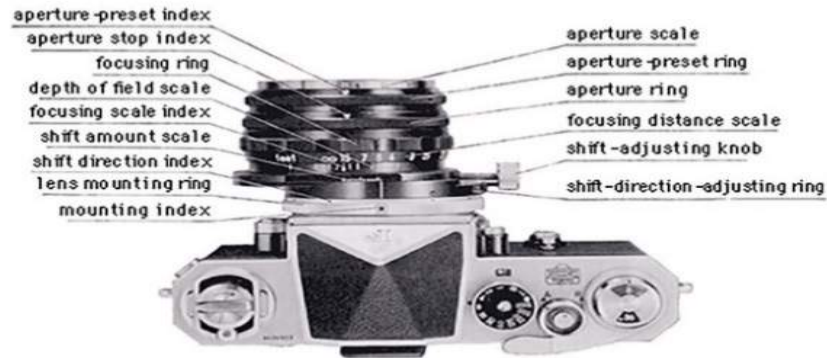


Figure 2-10. Diagram of PC-Nikkor lens from Nikon manual. (c.1963)

When taking photographs of any architectural elements, it is necessary to utilize a thoughtful programmatic approach through common sense and planning. The camera is a handy tool but only records what it can see, much the same way the human eye works. If you are unable to see a particular feature from one angle, the same applies to the camera (Figure 2-11 & 2-12). Considering this concept is paramount when establishing a project plan in prepping for photographic recording.

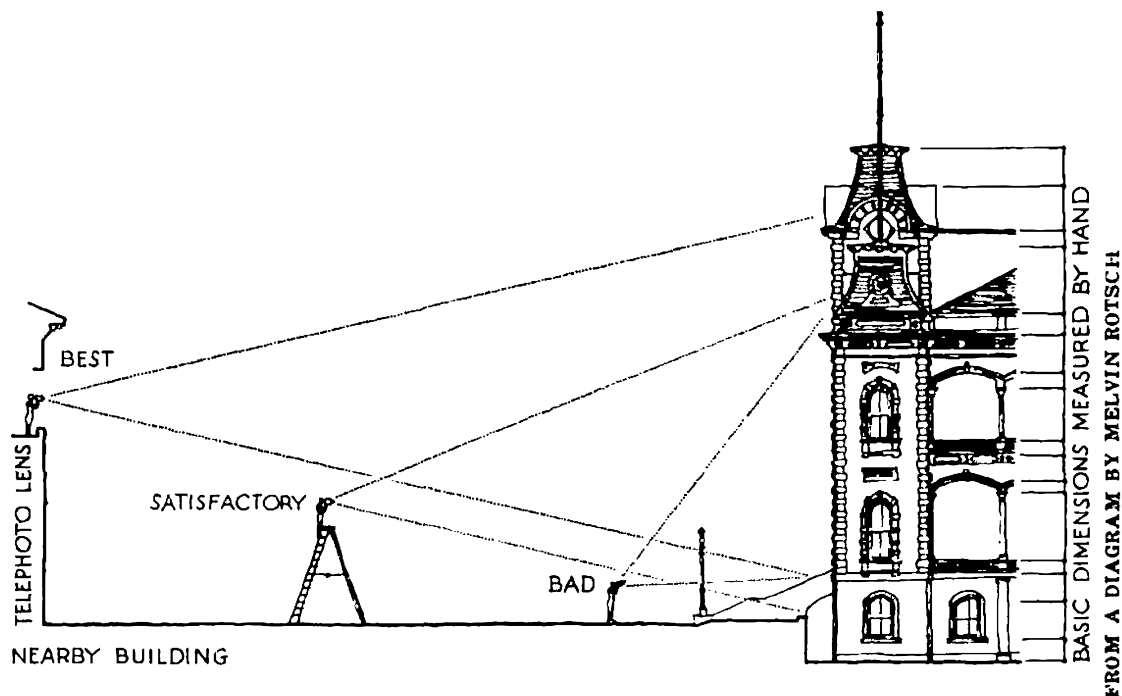


Figure 2-11. Proper positioning of a camera.

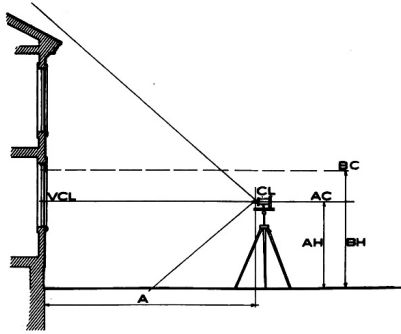


Figure 2-12. Camera location

CAMERA LOCATION:

"Find the exact center of the building Vertical Center Line (VCL) by measurement. Next, from equal distance points either side of the vertical center line (VCL), swing two equal arcs (Arc 1, Arc 2) about 50% longer than the distance from each side of the center. Connecting the point where the arcs intersect and the center of the building will give a line perpendicular to the building (CL/VCL)"²⁰

Photographs taken in the field would typically depend on a scale stick or measuring tape to provide an objectively accurate sense of the scale of the objects captured in an image (Figures 2-13 & 2-14).²⁰ In some instances, where irregularly shaped objects were the focus (e.g., stonework, log walls, and so on), a five foot-squared rigid grid system, constructed of pipe used in conjunction with a string grid at one-foot intervals, was used in place of a scale stick.²¹

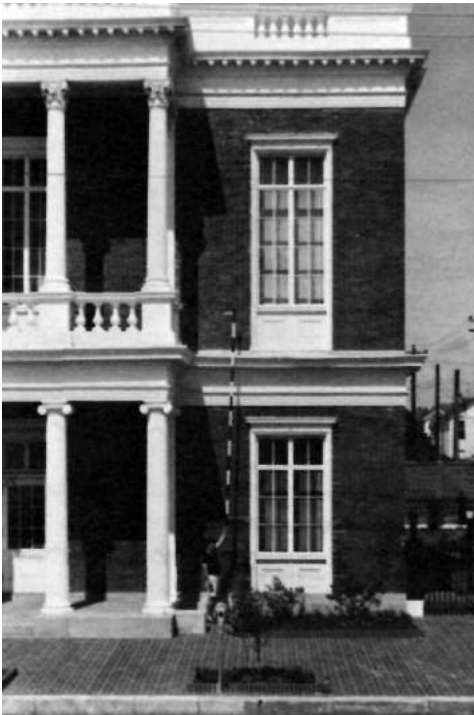


Figure 2-13. Use of scale stick in photo.



Figure 2-14. Detail of scale stick against bricks.

20 J. Henry Chambers, "Rectified Photography and Photo Drawing for Historic Preservation," draft, U.S. Department of the Interior, Heritage Conservation and Recreation Service, Office of Archaeology and Historic Preservation, (December 1973), 10, <http://hdl.handle.net/2027/mdp.39015006323771>. A great resource regarding the early process of photo rectification as observed by the DOI.

21 John A. Burns, *Recording Historic Structures*, 132.

Rectified photography is often useful in the creation of any drawing where details might not be clear or are missing. It is also often used to supplement the data derived from photogrammetry. Connecting the details from rectified photographs with information from a photogrammetric survey is possible. There is always an element of interpretation associated with the development of a measured drawing from the information recorded by the photogrammetric or rectified photography processes. This inherent degree of subjectivity requires the drawings to be made by those with not only a general understanding of architecture but also specific familiarity with historic buildings.²²

The Transition from Analog to Digital



Figure 2-15. Steven Sasson with his 1975 digital camera prototype



Figure 2-16. 1975 prototype of first digital camera

In 1975 Kodak engineer Steven Sasson developed the earliest digital camera (figures 15 & 16), a prototype device made from an amalgamation of computer and movie camera parts. The first promising digital camera sensors, developed during the 1980s, had a recording resolution of one megapixel. In 1987, Kodak developed a professional portable digital camera system (DCS), based on the Nikon F3 camera body (Figure 2-17).²³

²² Bernard M. Feilden, *Conservation of Historic Buildings*, 223.

²³ "History of the Digital Camera and Digital Imaging," History, Digitalkamera Museum, <https://www.digitalkameramuseum.de/en/history>.



Figure 2-17. Kodak DCS 100

While a shift from the purely analog to a more digital photogrammetric process began in the 1980s, 3D measurements for architectural applications still relied on digital scans of photographs produced mostly from single stereo image pairs.²⁴ By the 1990s, the reliance on film cameras in photogrammetry lessened with the introduction of some of the first practical digital cameras including improved sensors with higher resolution, of increasingly powerful personal computers, and of newer partially-automated photogrammetric software like Radr and PHOTOMOD.²⁵

24 Francesco Guerra, Laura Baratin, and Clemente Di Thiene, "Photogrammetric System and Cost Analysis for Architectural and Archeological Surveys," *Close-Range Photogrammetry Meets Machine Vision* 1395 (1990): , accessed April 27, 2019, doi:10.1117/12.2294252.

25 Yoichi Kunii and Hirofumi Chikatsu, "Application of the Three-million-pixel Consumer Camera to Digital Photogrammetry," *Videometrics and Optical Methods for 3D Shape Measurement* 4309 (2000): , accessed April 27, 2019, doi:10.1117/12.410884.

Alain Chapuis, "Developments in Digital Photogrammetry and a Description of the Flow of Data through a Digital Photogrammetric System," *Digital Photogrammetry and Remote Sensing* 95 2646 (1995): , accessed April 27, 2019, doi:10.1117/12.227885.

2.2 History of Digital Photogrammetry

The Technological Developments Behind Digital Photogrammetry

Digital photogrammetry represents a significant evolution of the way in which traditional theories of photogrammetry can be applied. The same basic principles of geometry and other pertinent mathematics still apply. However, it is only with the resources and concepts applied in the latter half of the 21st century that the relationships between photographs and the features of real-world objects can be further exploited by providing a more practical and efficient workflow, paving the way for new, complex, and exciting purposes.

Traditional photogrammetric techniques for documentation proved clumsy and time-consuming. Often the impractical nature of its very basic implementation was perceived to be a burden outweighing any perceived usefulness as an architectural tool. It often took more effort and valuable time to produce outputs achieved by other traditional methods. It wasn't until the advent of powerful computer systems in the 1980s that the road to digital photogrammetry was first navigable.

The initial groundwork for a digital photogrammetric workflow began with the innovative computer programming of feature-detecting language, supported by algorithms which made possible the relatively precise matching of unique points between multiple images. Feature detection is a fundamental tenet of digital photogrammetry

The 3D models produced by today's robust combinations of hardware and software all have a basis on this foundational concept. Visual features are the unique identifiers which allow computers to identify the natural relationships between one image and another, and ultimately the difference between individual objects within those images. The greater the correlation between features of one image and the images of an entire image set, the higher the potential for more efficient, accurate, and useful output.

Image feature matching is intrinsically bound to the beginnings and rapid evolution

of computer vision. The gap between feature-detection accuracy and computational efficiency is closing, making possible a more efficient digital photogrammetric process. Image feature matching is the proverbial glue for it all.

Development of Digital Image Feature Matching

The concept behind digital image matching was first successfully implemented by Hans P. Moravec at Carnegie-Mellon University in 1980. Moravec's project had no connection to the science of photogrammetry. Instead, Moravec, a computer scientist and mathematician, had a goal to digitally program a robotic TV cart (Figure 2-18), found in his lab, so that it could navigate obstacles deliberately placed in its path. To make this possible, Moravec developed what he termed the robot's "avoidance system," which relied on a TV camera to track the robot's position in the real world.²⁶

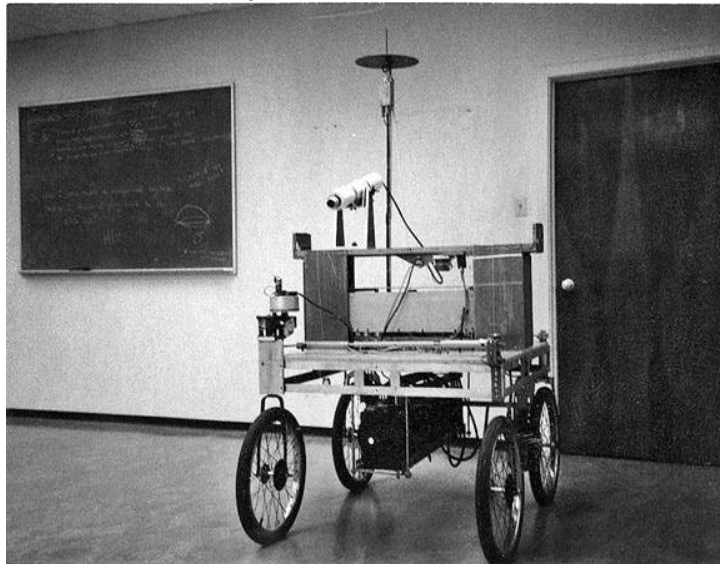


Figure 2-18. Moravec's TV cart, 1979.

Images from the TV camera were digitally converted to be compared in real-time by a computer system. An algorithm developed as part of a proprietary computer program handled the real-time analysis of the images during their capture. It worked by determining and then comparing similar points within sub-regions of images. For this to

²⁶ Hans P. Moravec, "Rover Visual Obstacle Avoidance," in *Proceedings of the 7th International Joint Conference on Artificial Intelligence - Volume 2* (Morgan Kaufmann Publishers Inc., 1981), 785–786.

work, a set of images was required to determine the exact location and correlation of the points accurately, and therefore to assess the location of objects within the path of the robot. While this image-matching system was successful, it had flaws. It was slow and not always accurate, with occasional mismatches of image features. Moravec's algorithm became known as a corner detector, best at detecting edges (Figure 2-19) located at the corners of objects.²⁷

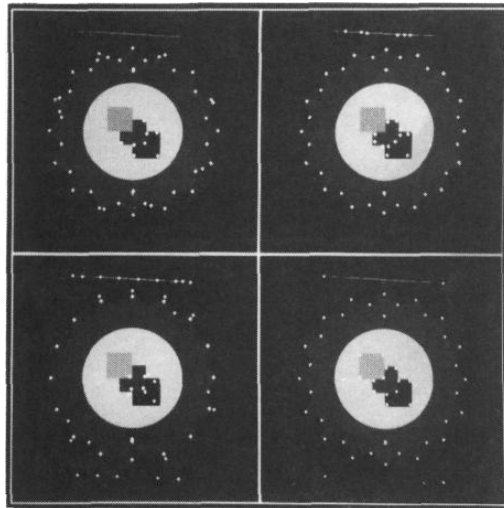


Figure 2-19. Moravec corner detection in comparison with similar period edge-detecting operators
by Beaudet and Kitchen & Rosenfeld.

Image matching leaped forward with the work of Harris and Stephens, in 1988, known as Alvey Project MMI149. Their project improved upon the level of edge detection seen in Moravec's earlier work by enabling the tracking of edges through classifying regions of high contrast, and by evaluating the quality of the pixels which corresponded with both corners and other solid edge areas. This tweak to Moravec's findings proved much more reliable and accurate.²⁸ These types of feature detectors were still commonly referred to as corner detectors despite their ability to track other image locations; their major limitation was that they were only reliable when comparing images of a set scale.²⁹

²⁷ Moravec, "Rover Visual Obstacle Avoidance," 785–786.

²⁸ Ibid.

²⁹ David G. Lowe, "Distinctive Image Features from Scale-Invariant Keypoints," *International Journal of Computer Vision* 60, no. 2 (2004): 91–110.

Beyond the Initial Applications of Feature Matching

The initial applications of these corner detectors were for stereo and short-range tracking of motion. Application of these operations to more challenging problems happened over time. By 1995, multiple teams of programmers were working on distinct approaches to more elaborate feature matching. Larger areas were sampled around features to locally correlate points from one image to another in more massive image sets.³⁰

One such approach focused on a two-pronged strategy; initial matches stemmed from a process of correlation (through corner detecting) and relaxation (through feature continuity and uniqueness), followed by a more robust method, known as Least Median of Squares (LMedS), to discard false matches.³¹

In 1995, P.H.S. Torr, of the University of Oxford, developed another approach to establish matches. Torr's approach focused on long-range motion matching, which applied explicitly to matching geometric constraints on moving images. This approach was also multi-faceted, using mixed strategies and several algorithms in multiple stages to achieve accurate results.³²

Matching Features within a Larger Image Database

With the rapid advancement of algorithms from the late 1980s through the 1990s, analysis of more challenging datasets was feasible. Processes that until this point in time were rather slow to calculate were now able to be more efficiently handled and even more accurately matched.

³⁰ Ibid., 3.

³¹ Zhengyou Zhang et al., "A Robust Technique for Matching Two Uncalibrated Images through the Recovery of the Unknown Epipolar Geometry," *Artificial Intelligence* 78, no. 1–2 (1995): 87–119.

³² Philip Hilaire Sean Torr and David W. Murray, *Motion Segmentation and Outlier Detection*, 1995.

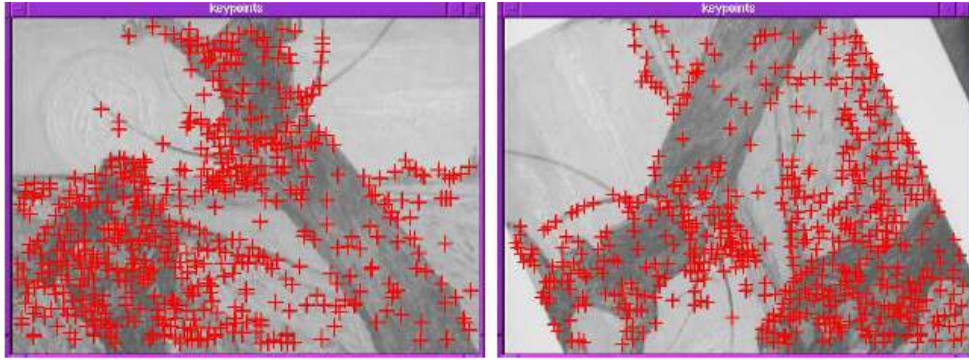


Figure 2-20. Interest points detected on the same scene under rotation as realized by Schmid & Mohr, 1997.

Possibly one of the most revolutionary improvements in image matching came in 1997 in a matching scheme developed by Schmid and Mohr (Figure 2-20), considered by peers as ground-breaking.³³ That team solved the problem of matching a single image to a broad set of images, where images (or the objects in them) are not necessarily orientated in the same way. They used what is known as a rotationally invariant descriptor. Their multidimensional technique also was able to handle scale change, small viewpoint variations, partial visibility, and even extraneous features, albeit for general recognition only.³⁴

Just two years later, in 1999, the man whose work led to an algorithm which is relied upon heavily in some of today's most popular photogrammetry software programs extended the approach of local adaptation (as seen in Harris' corner detector) to achieve matching with image scale invariance.³⁵ David Lowe, the developer of this approach, called this method scale invariant feature transformation (SIFT).

SIFT can match incredibly large numbers of features between images with a great ability to handle other variations in the images themselves rather robustly. It was during the development of SIFT that the potential for the reconstruction of 3D digital models from multiple images in a given data set was a possibility. Additional issues such as occlusion (partial obscuring of an object) and other extraneous image clutter were no

³³ Lowe, "Distinctive Image Features from Scale-Invariant Keypoints," 3.

³⁴ Schmid and Mohr, "Local Grayvalue Invariants for Image Retrieval."

³⁵ Lowe, "Distinctive Image Features from Scale-Invariant Keypoints," 3.

longer the challenges seen in previous iterations of feature matching algorithms.³⁶

The success of SIFT arises from its ability to do several things differently and more efficiently than previous feature matching algorithms. Perhaps the most important differentiation is SIFT's ability to define and match key points with sub-pixel accuracy. The key points can be defined even within blurry or noisy images, and their computation is highly efficient with substantially reduced processing times and unprecedented levels of accuracy. Object isolation among extraneous clutter is intelligently assessed and realized. It is the accommodating and flexible nature of SIFT that set the stage for others to realize actual 3D object reconstruction.³⁷

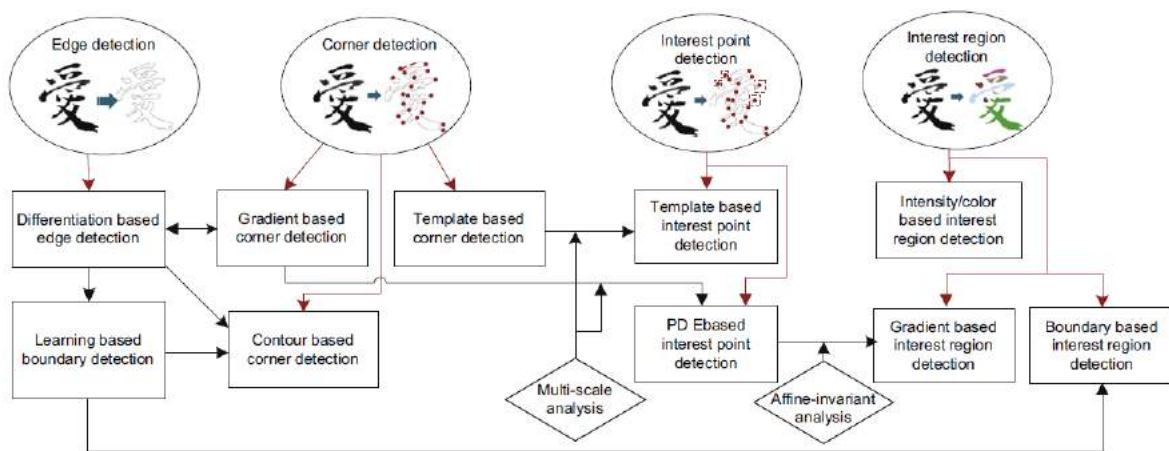


Figure 21. Classification and hierarchy of visual image feature detection methods.

Considerable progress in every aspect of image feature mapping since the development and maturation of Lowe's SIFT algorithm has transpired (Figure 2-21). Corner and edge detection making up but two categories of feature mapping methods. Beyond them, there are now refined variants and ways of combining new methods with old ones. Namely, they fall under what is known as blob detection (interest point detection and region detection).³⁸

Blob detection focuses around recognizing relationships within a region of similar

36 David G. Lowe, "Object Recognition from Local Scale-Invariant Features - IEEE Conference Publication," accessed December 14, 2018, <https://ieeexplore.ieee.org/document/790410>.

37 Lowe, "Distinctive Image Features from Scale-Invariant Keypoints," 2–3, 25.

38 Ibid., 737–738.

pixels, what is known as “surrounding neighbors.” The basis for blobs themselves is on the dependability of various interest properties, which refers to the identification of interest points (key points) and interest regions (key regions). How the detection methods are exploited and relied upon vary tremendously and are typically enhanced by their dependent integration through the latest advancing amalgamations of detection algorithms, as seen in the chart below.³⁹

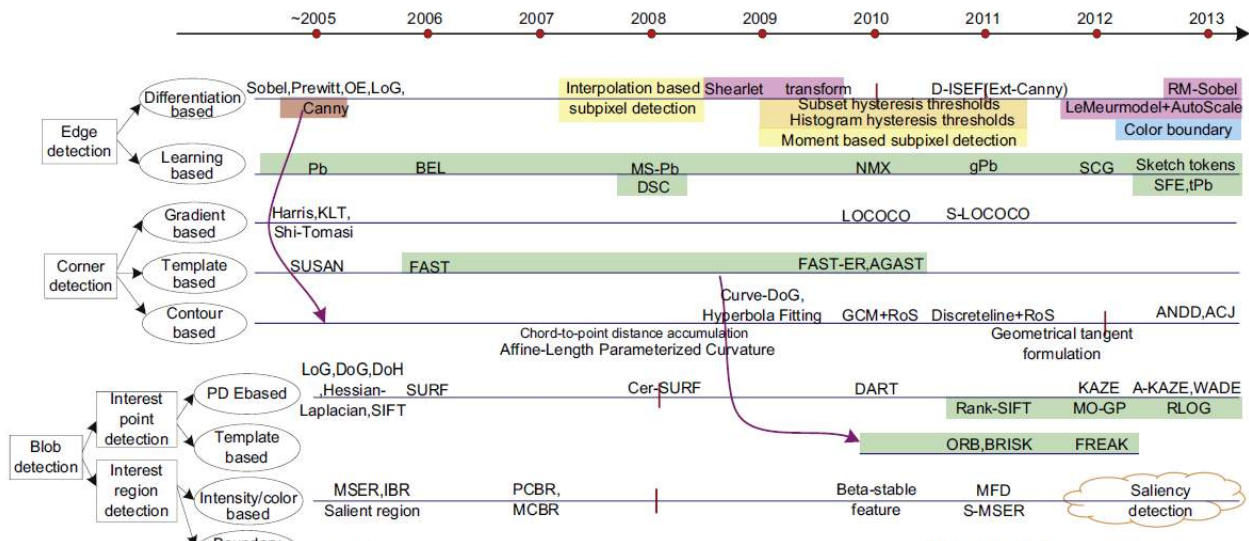


Figure 22. Recent advances in visual feature detection.

Image feature detection continues to evolve and is becoming increasingly complex (Figure 2-22). The results of the evolution in approach, theory, and technological advancement present a growing and seemingly unlimited potential for 3D documentation through photogrammetry. Existing photogrammetry software is continually updated, and new software developed based on these feature matching improvements. The gap between detection accuracy and computational efficiency grows smaller with every forward-moving pursuit. Image feature mapping remains the glue to the untapped potential behind the processing of 3D photogrammetric computer-based visualizations.

39 Li et al., “A Survey of Recent Advances in Visual Feature Detection.”

3 Equipment & Workflow

3.1 Testing Unique Equipment

Choosing My Equipment (Camera Systems and Interchangeable Lenses)

Accessibility & Feasibility of Equipment

This aspect of the thesis considers the technical variables that impact the photogrammetric process, and focuses on criteria such as accessibility, time, and cost with respect to image quality and utility for conservation. The equipment used can be purchased directly from retail outlets, but also, in many cases, can be rented. Renting equipment is a simple and effective means of maintain project costs with a practical “everyday” project budget.

Camera Systems

Capturing the images for a photogrammetric dataset is the most crucial step in the entire workflow. Hence, choosing the imaging equipment is a critical decision. Digital camera technology has continued to steadily evolved. Annually, the leading imaging equipment manufacturers release multiple new camera models; on occasion, they also develop entirely new systems.

The imaging equipment described here was selected to test whether newer camera technology equates to better, more detailed, and more quickly produced models, and to determine what effect image sensor size has on the results. The cameras ultimately chosen represent a range of systems produced recently and, in one case, a decade ago. Each camera also represents a different photographic format, that is, they had varying physical sensor sizes. Larger sensors register more information and produce better quality images.

The camera’s chosen (arranged left to right, from smallest to largest sensor size)

are as follows: iPad Pro 10.5" (2017), Canon EOS 7D (2009), Nikon D850 (2017), and a Phase One XF with an iQ4 151-megapixel digital back. The Canon, now over a decade old, was once at direct retail cost around twice that of the iPad (currently about half this, if purchased, used), the Nikon about two and half times over the Canon's original price, and the Phase One being nearly 17 times the present expense of the Nikon. The variation in cost directly correlates to each camera's sensor size as well as some associated specifications particular to each design.

iPad Pro 10.5" (2017)



Figure 3-1. Apple iPad Pro 10.5-inch

Sensor

Dimensions: 4.8 x 3.6mm

Maximum Resolution: 2048 x 1536, 12MP

Fixed 35mm Focal Length: 28mm

The rear-facing camera on this iPad Pro model has a resolution of 12-megapixel with a backside illumination sensor and an aperture of f1.8. It features optical image stabilization with a six-element lens and a digital zoom up to 5X.¹ The camera is the same variety as can be found in an iPhone 7, praised after its release in multiple product reviews. The device has average dynamic range, and is thus commonly considered to be a competent camera, recognizing that the camera unit is an integrated component of a more intricate mobile device.² Controlling the camera with a third-party app is possible and provides additional functionality similar to the controls ordinarily associated with dedicated camera systems. For testing, I used only the default camera application.

¹ "iPad Pro (10.5-inch) – Technical Specifications," Blog, Eric Kim Photography, accessed April, 2, 2019, <http://erickimphotography.com/blog/2018/04/07/review-of-the-ipad-pro-10-5-inch-camera-for-photography/>

² Eric Kim, "Review of the iPad Pro 10.5 Inch Camera for Photography," Support, Apple Inc., accessed April, 2, 2019, https://support.apple.com/kb/SP762?locale=en_US.


Cost		
<u>MSRP at Launch</u>	<u>Current Used Average</u>	<u>Refurbished</u>
\$729	\$600	\$559

Canon EOS 7D (2009)**Figure 3-2.** Canon EOS 7D**Sensor****Dimensions:** 22.3 x 14.9mm**Maximum Resolution:** 5184 x 3456, 18MP**Format:** APS-C (Cropped Sensor, "Small Format")

Since its release in 2009, the Canon EOS 7D has become one of this company's most popular small format APS-C DSLRs among serious photographers. This camera works with interchangeable lenses (EF/EF-S), allowing the photographer to control the quality, focal length, and other optical characteristics when capturing photos. The sensor itself is an 18MP CMOS sensor which employs Canon's proprietary dual DIGIC 4 Image Processors. The EOS 7D is a ruggedly constructed instrument appropriate for practical in-field usage; the body is fabricated from a durable magnesium alloy which includes dust and weather-sealing. The shutter has an average life expectancy of 150,000 cycles.³

³ "EOS 7D," Products, Canon U.S.A. Inc., accessed April, 4, 2019, <https://www.usa.canon.com/internet/portal/us/home/products/details/cameras/eos-dslr-and-mirrorless-cameras/dslr/eos-7d>.

Cost (Camera Body Only)	
<u>MSRP at Launch</u>	<u>Current Used Average</u>
\$1699	\$450

Lenses Used with the Canon			
<p>Canon EF 17-40mm f/4L USM</p>	<u>MSRP at Launch</u>	<u>Current New Price</u>	<u>Current Used Average</u>
	\$799.99	\$499.99	\$400
			
<p>Figure 3-3. Canon EF 17-40mm.</p>			
<p><u>Features⁴</u></p>			
<p>Focal Length & Maximum Aperture: 17 - 40mm; 1:4 Lens Construction: 12 elements in 9 groups Diagonal Angle of View: 104° - 57° 30' Focus Adjustment: Inner focusing system with USM Closest Focusing Distance: 0.28m / 0.9 ft. Zoom System: Rotating type Filter Size: 77mm Max. Diameter x Length, Weight: 3.3 x 3.8, 1.1 lb. / 83.5 x 96.8mm, 500g</p>			

⁴ "EF 17-40mm f/4L USM," Products, Canon U.S.A., Inc., accessed April, 4, 2019, <https://www.usa.canon.com/internet/portal/us/home/products/details/lenses/ef/ultra-wide-zoom/ef-17-40mm-f-4l-usm/ef-17-40mm-f4l-usm>.

Lenses Used with the Canon			
	<u>MSRP at Launch</u>	<u>Current New Price</u>	<u>Current Used Average</u>
	\$799.99	\$599.99	\$600
<p>Canon EF 70-200mm f/4L USM</p>			
	<p>Figure 3-4. Canon EF 70-200 f/4L USM</p>		
	<p><u>Specifications⁵</u></p>		
	<p>Focal Length & Maximum Aperture: 70-200mm 1:4.0 Lens Construction: 16 elements in 13 groups Diagonal Angle of View: 34° - 12° Focus Adjustment: Inner focusing system with USM Closest Focusing Distance: 1.2m / 3.9 ft. Zoom System: Rotating type Filter Size: 67mm Max. Diameter x Length, Weight: 3.0 x 6.8, 25 oz. / 76mm x 172mm, 705g</p>		

⁵ "EF 70-200mm f/4L USM," Products, Canon U.S.A., Inc., accessed April, 4, 2019, <https://www.usa.canon.com/internet/portal/us/home/products/details/lenses/ef/telephoto-zoom/ef-70-200mm-f-4l-usm/ef-70-200mm-f4l-usm>.

Nikon D850 (2017)



Figure 3-5. Nikon D850.

Sensor

Dimensions: 35.9 x 24mm

Maximum Resolution: 8256 x 5504, 45.7MP

Format: Full-frame 35mm system

The Nikon D850 houses a back-side illuminated (BSI) full-frame CMOS image sensor with a total effective resolution of 45.7 megapixels. The camera has no optical low-pass filter, and thus the sharpest image possible, (this function limits the performance to a noticeable degree in other cameras). The D850 utilizes Nikon's EXPEED 5 image processor; it produces minimal noise, has an impressively wide dynamic range, and, hence, records a more representative gamut of real-life colors. Similar to the Canon, this camera has a solid weather-sealed body.⁶

⁶ "D850 Overview," DSLR Cameras, Nikon Inc., accessed April, 4, 2019, <https://www.nikonusa.com/en/nikon-products/product/dslr-cameras/d850.html>.

Cost (Camera Body Only)	
<u>MSRP at Launch</u>	<u>Current Used Average</u>
\$3299	\$2750

Lenses Used with the Nikon			
AF-S NIKKOR 24mm f/1.4G ED	<u>MSRP at Launch</u>	<u>Current New Price</u>	<u>Current Used Average</u>
	\$1,999.95	\$1,999.95	\$1,100
			
Figure 3-6. AF-S NIKKOR 24mm f/1.4G ED			
<u>Features⁷</u>			
Focal Length & Maximum Aperture: 24mm; 1:4 Lens Construction: 12 elements in 10 groups Diagonal Angle of View: 84° Focus Adjustment: Automatic, manual Closest Focusing Distance: 9.8in Zoom System: n/a Filter Size: 77mm Max. Diameter x Length, Weight: 3.3 in. (83 mm) x 3.5 in. (88.5 mm), 21.9 oz. (620 g)			

⁷ "AF-S NIKKOR 24mm f/1.4G ED Overview," Camera Lenses, Nikon Inc., accessed April, 4, 2019, <https://www.nikonusa.com/en/nikon-products/product/camera-lenses/af-s-nikkor-24mm-f%252f1.4g-ed.html>

Lenses Used with the Nikon			
	<u>MSRP at Launch</u>	<u>Current New Price</u>	<u>Current Used Average</u>
	\$1,799	\$1,619	\$1,350
ZEISS Milvus 1.4/85			
	<p>Figure 3-7. Zeiss Milvus 1.4/85</p> <p style="text-align: center;"><u>Features⁸</u></p> <p>Focal Length & Maximum Aperture: 85mm; 1:4 Lens Construction: 11 elements in 9 groups Diagonal Angle of View: 29° / 24° / 16° Focus Adjustment: Manual Closest Focusing Distance: 0,80 m (31.5") Zoom System: n/a Filter Size: 77mm Max. Diameter x Length, Weight: 89 mm (3.49") x 119 mm (4.69"), 21.9 oz. 1.210 g (42.68 oz)</p>		

⁸ "ZEISS Milvus 1.4/85," Milvus Lenses, Zeiss United States., accessed April, 4, 2019, <https://www.zeiss.com/camera-lenses/us/photography/products/milvus-lenses/milvus-1485.html>.

Phase One XF IQ4 150MP



Figure 3-8. Phase One XF IQ4 150MP

Sensor (iQ4 150MP)

Dimensions: 53.4 x 40mm

Maximum Resolution: 14204 x 10652, 151MP

Format: Full-frame medium-format system

The Phase One XF is a modular camera system, similar to older film-based medium format systems. Upgradeability is an advantage of such systems, as components on the camera are easy to replace (e.g., the viewfinder and digital back). The XF camera body accepts various digital backs. It's compatible with backs made by Phase One in addition to other manufacturers, including older digital backs (which cost significantly less than newer models). Currently, there is no comparable alternative which matches the resolution of this sensor. The XF camera body appears less rugged than that of the Canon or Nikon; the materials feel plastic-like. It is not marketed as being weather resistant. An advantage, however, is the lack of a shutter in the camera body, as the shutter is built into

the lenses which can be mounted to the camera; this equates to greater longevity of the entire system.⁹

Cost (Camera Body Only)	
<u>MSRP at Launch</u>	<u>Rental Rates</u>
\$51,990	\$820/day, \$2460/week, \$7380/month

⁹ "XF IQ4 150MP Achromatic Camera System," IQ Digital Backs, Phase One A/S., accessed April, 4, 2019, <https://www.phaseone.com/en/Photography/IQ-Digital-Backs/IQ4/XF-IQ4-150MP-Achromatic-Camera-System>.

Lenses Used with the Phase One			
Schneider Kreuznach 45mm LS f/3.5	MSRP at Launch	Rental Rates	Current Used Average
	\$5,990	\$100/day, \$300/wk, \$900/mo.	\$4,900
			
Figure 3-9. Schneider Kreuznach 35mm LS f3.5			
<u>Features</u> ¹⁰			
Focal Length & Maximum Aperture: 45mm; 3.5 Lens Construction: 10 elements in 7 groups Diagonal Angle of View: 73°/62°/48°84° Focus Adjustment: Autofocus, manual Closest Focusing Distance: 55cm / 1.80ft Zoom System: n/a Filter Size: 95mm Max. Diameter x Length, Weight: 101 x 122.9mm / 4.0 x 4.8”			

¹⁰ “Schneider Kreuznach 45mm LS f/3.5,” Lenses, Phase One A/S, accessed April, 4, 2019, <https://www.phaseone.com/en/Photography/XF-Camera-System/Lenses/Schnieder-Kreuznach-45mm-Blue-Ring>.

Lenses Used with the Phase One			
Schneider Kreuznach 150mm f/2.8 LS BR	MSRP at Launch	Rental Rates	Current Used Average
	\$6,990	\$100/day, \$300/wk, \$900/month	\$5,400
			
<p>Figure 3-10. Schneider Kreuznach 35mm LS f3.5</p>			
<p><u>Features</u>¹¹</p>			
<p>Focal Length & Maximum Aperture: 150mm; 2.8 Lens Construction: 8 elements in 7 groups Diagonal Angle of View: 25° Focus Adjustment: Autofocus, manual Closest Focusing Distance: 1.0m / 3.28ft Zoom System: n/a Filter Size: 95mm Max. Diameter x Length, Weight: 115 x 141.6mm / 4.5 x 5.6", 1.658g / 3.65lb</p>			

¹¹ "Schneider Kreuznach 45mm LS f/3.5," Lenses, Phase One A/S, accessed April, 4, 2019, <https://www.phaseone.com/en/Photography/XF-Camera-System/Lenses/Schneider-Kreuznach-150mm-Blue-Ring>.

Digital Camera Sensors

To understand the substantial differences between these systems, one needs to know something about the technology behind them. One of the most significant features of a digital camera is its sensor. It is essentially the camera's brain. Different systems have different sized sensors.

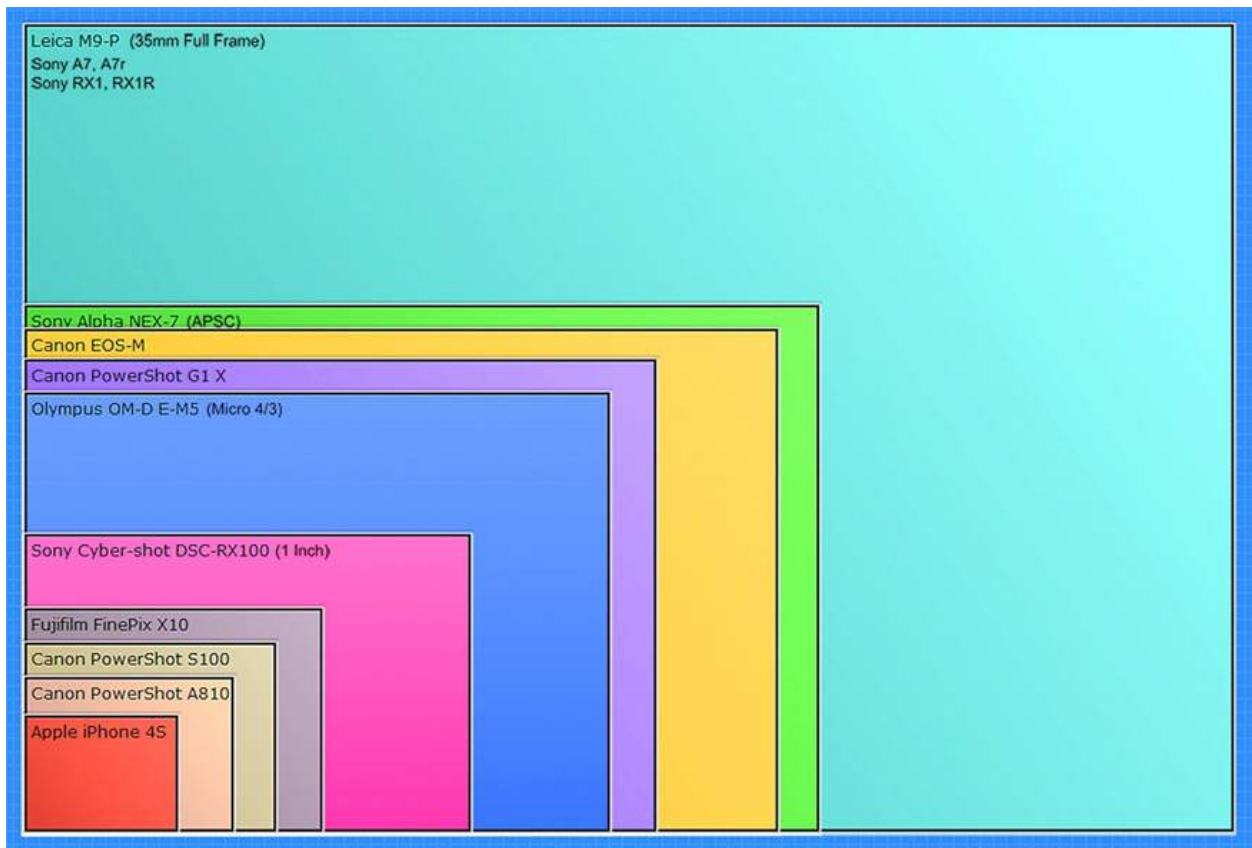


Figure 3-11. Camera Sensor Size Compared

The red rectangle at the bottom left (Figure 3-11) represents the size of the sensor in the iPad. The bright green square is the sensor from the Canon, and the large blue rectangle is the sensor in the Nikon.

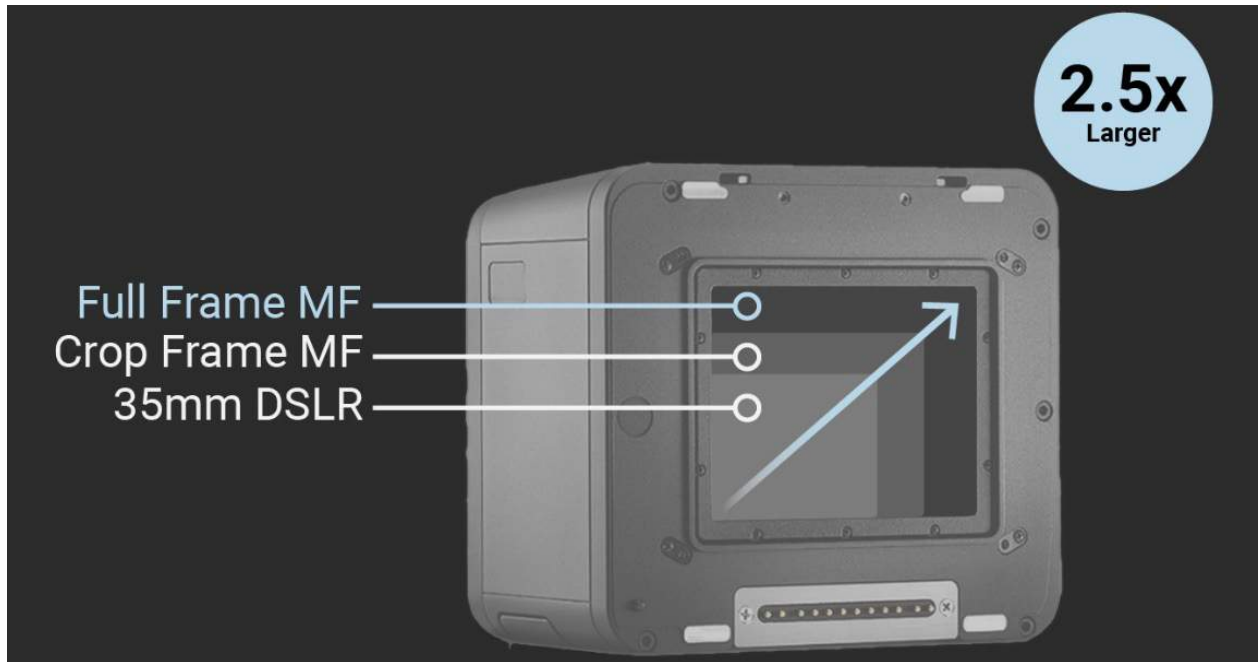


Figure 3-12. 35mm camera sensor compared to a full fram medium format sensor.

The image above (Figure 3-12) illustrates that the sensor in the full frame medium-format Phase One is actually two and a half times larger than the sensor in the 35mm Nikon. This is significant. It means that of all the cameras being tested, the medium-format Phase One is capable of recording far more detail not only in terms of resolution but color information as well. Having a much greater dynamic range, this also means that it captures that much more of a scene than a smaller sensor can.

Lenses

Along with the cameras, the lenses chosen for the project had to be considered with some level of scrutiny. All but the iPad can accept interchangeable lenses. A lens is the eye of the camera. With the advent of higher resolution sensors, the choice of a lens has a major impact on the final image. Focal length is an important factor to consider. Wide angle lenses, those with a focal length of 35mm or wider, capture the greatest portion of a given scene. Normal to telephoto lenses, 50mm and up, capture less of the scene, as they magnify things to varying extents. The images that follow (figures 13 & 14) relate focal length and angle of view, demonstrating how these control just how much scenic information the camera records. For photogrammetry, it is optimal to use one and sometimes two focal lengths [typically, a wide angle, such as 24 or even 35 millimeters and something in the shorter telephoto range like an 85 and up to 200 mm]. Prime lenses are preferred over zooms because primes have a fixed focal length and therefore avoid the problem of accidentally shifting the focal length while shooting.

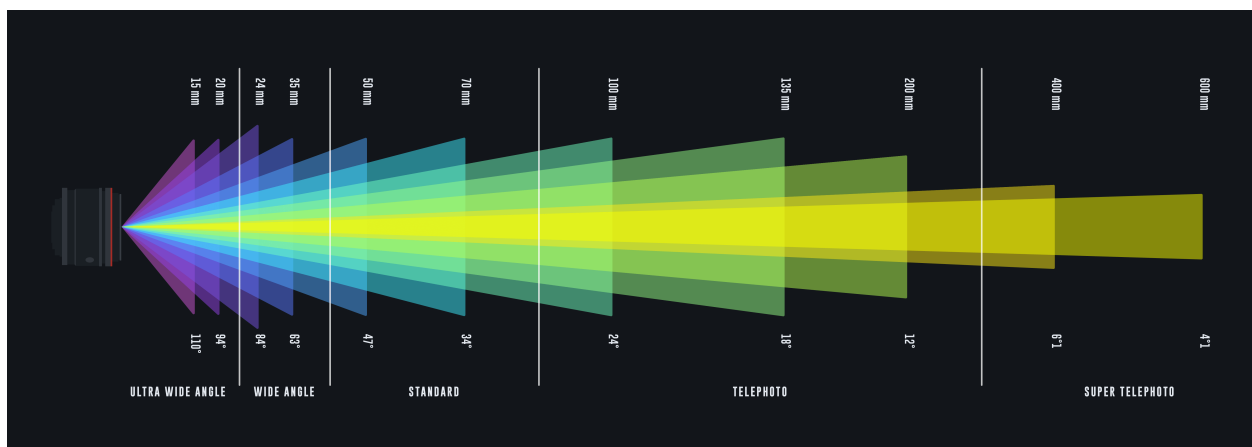


Figure 3-13. Focal length and field of view visualized.



Figure 3-14. Effect of differing focal lengths on an image.

Other Equipment



Figure 3-15. Example of equipment used for experiments.

Other equipment (Figure 3-15) used the research served to support the use of the cameras in the field and to aid in digital model production. As seen above, a video slider for maintaining camera stability allows for consistent photo overlap (a critical photogrammetric principle). At least 60% overlap is encouraged and as high as 90% is used to guarantee the best results. The slider also makes it easy to record horizontal surfaces, as seen here. Additionally, an xRite ColorChecker Passport (color chart) was used. In some instances, (where lighting is uneven) the use of a flash unit is necessary. A remote shutter release was also essential for avoiding camera shake when actuating the camera's shutter, and a machinist's rule to provide precision measurements for the scaling to be done in the processing stage.

3.2 Evaluation & Selection of Current Photogrammetric Software

Choosing Software for Testing

As to the software for photogrammetry, there is an abundance of options to choose from. New programs are available nearly every year, making it a difficult choice for anyone, especially for those less familiar with the subject. The programs chosen for this research take this concern into account and were selected for several primary reasons: popularity (common use among professionals); varying price points (those that either require a subscription, can be purchased outright, or are completely free); age (latest vs well-established); user-friendly applications (all-in-one, stand-alone programs able to, at some level, automatically generate models with very little user input); and perhaps most importantly, this writer's own personal familiarity and access to them.

For this project, five total programs were selected for analysis. The programs have been tested as consistently as possible to determine speed and efficiency of operation, and to reveal which programs offer the most detailed and suitable end product for various architectural conservation applications. Models of architectural elements have been produced using the default settings of each program, as well as rendering them at each program's highest level of detail possible. The results have been analyzed by both qualitative and quantitative study and will be weighed along with factors of practicality, availability, cost, etc.

Metashape by Agisoft

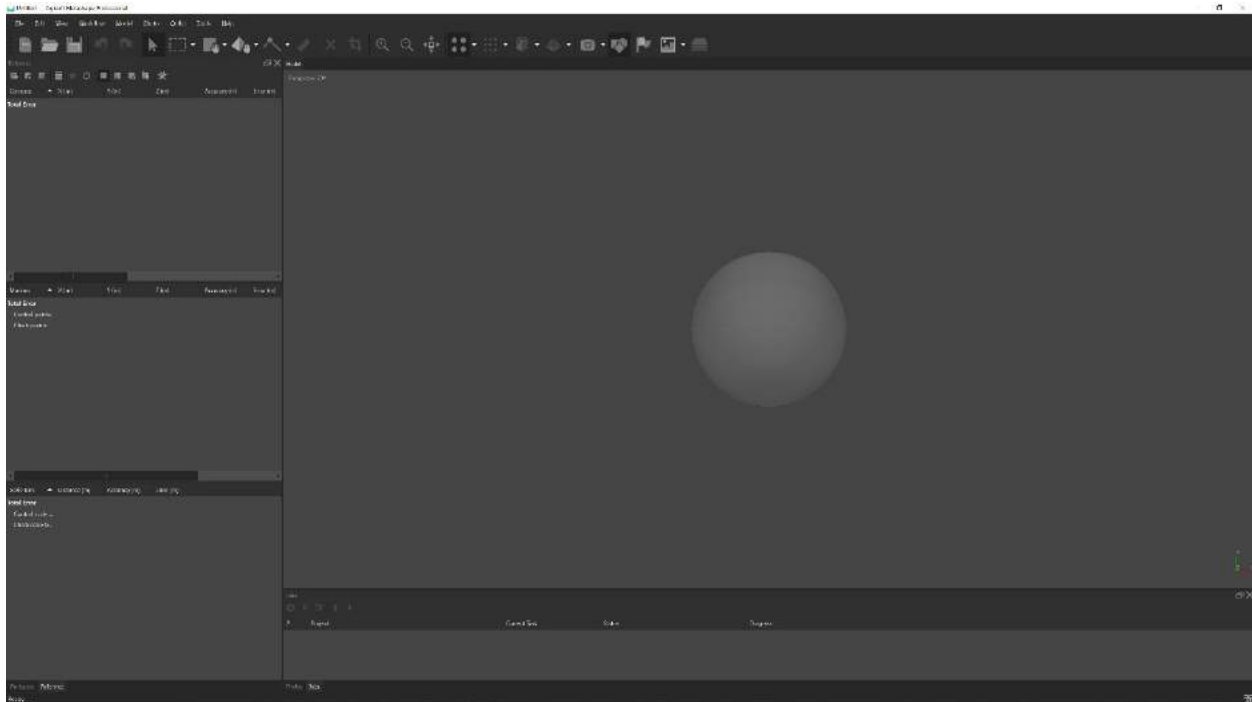


Figure 3-16. User interface of Metashape by Agisoft.

Among the best known photogrammetry applications today, Agisoft Metashape (previously PhotoScan - Figure 3-16) has been around for more than a decade. Metashape is one of those tried and true programs that essentially pioneered the way for the myriad of other stand-alone applications which exist now. It is the program through which many were introduced to digital photogrammetry.¹²

Metashape has the ability to process digital imagery from both aerial (drones) and terrestrial cameras. It can handle the input of different camera and lens types through automatic calibration of the data. Specific abilities of the professional version of the program include the capacity to customize settings related to each of the main functions of the program. For example, Metashape can produce digital elevation models, and georeferenced orthomosaic photos; inbuilt tools allow for direct measurements of distances, areas, and volumes; the importation of ground control points (GCPs) from

12 "History," About, Agisoft, accessed March, 31, 2019, <https://www.agisoft.com/about/>.

existing survey data provides a capacity for greater precision. Beyond this, the program offers the potential to generate custom Python scripting for streamlining project workflows, 3D and 4D (advanced visual data for games, cinema, etc.); panoramic stitching is also possible and requires a minimum of two camera stations; multi-spectral imagery (i.e. infrared) can also be processed. Notably, the Metashape can utilize distributed data processing over a grid of computer workstations (by harnessing the power of multiple computers over a network, processing times can be significantly reduced).¹³

Cost¹⁴	
Professional Edition	Standard Edition
\$3499*	\$179*
<i>*Free Updates included for the lifetime of the product. Educational and Floating Licenses are available for special prices.</i>	

13 "Professional Edition," Features, Agisoft, accessed March, 31, 2019, <https://www.agisoft.com/features/professional-edition/>.

14 "Buy," Online Store, Agisoft, accessed March, 31, 2019, <https://www.agisoft.com/buy/online-store/>.

System Requirements¹⁵		
Basic Configuration (up to 32 GB RAM)	Advanced Configuration (up to 64 GB RAM)	Extreme Configuration (more than 64 GB RAM)
<p><u>CPU:</u></p> <p>Quad-core Intel Core i7 CPU, Socket LGA 1150 or 1155 (Kaby Lake, Skylake, Broadwell, Haswell, Ivy Bridge or Sandy Bridge)</p> <p><u>Motherboard:</u></p> <p>Any LGA 1150 or 1155 model with 4 DDR3 slots and at least 1 PCI Express x16 slot</p> <p><u>RAM:</u></p> <p>DDR3-1600, 4 x 4 GB (16 GB total) or 4 x 8 GB (32 GB total)</p> <p><u>GPU:</u></p> <p>Nvidia GeForce GTX 980 or GeForce GTX 1080 (optional)</p>	<p><u>CPU:</u></p> <p>Octa-core or hexa-core Intel Core i7 CPU, Socket LGA 2011-v3 or 2011 (Broadwell-E, Haswell-E, Ivy Bridge-E or Sandy Bridge-E)</p> <p><u>Motherboard:</u></p> <p>Any LGA 2011-v3 or 2011 model with 8 DDR4 or DDR3 slots and at least 1 PCI Express x16 slot</p> <p><u>RAM:</u></p> <p>DDR4-2133 or DDR3-1600, 8 x 4 GB (32 GB total) or 8 x 8 GB (64 GB total)</p> <p><u>GPU:</u></p> <p>Nvidia GeForce GTX 980 Ti, GeForce GTX 1080 or GeForce TITAN X</p>	<p>For the processing of extremely large data sets a dual socket Intel Xeon Workstation can be used.</p>

¹⁵ "Downloads," System Requirements, Agisoft, accessed March, 31, 2019, <https://www.agisoft.com/downloads/system-requirements/>.

RealityCapture by Capturing Reality

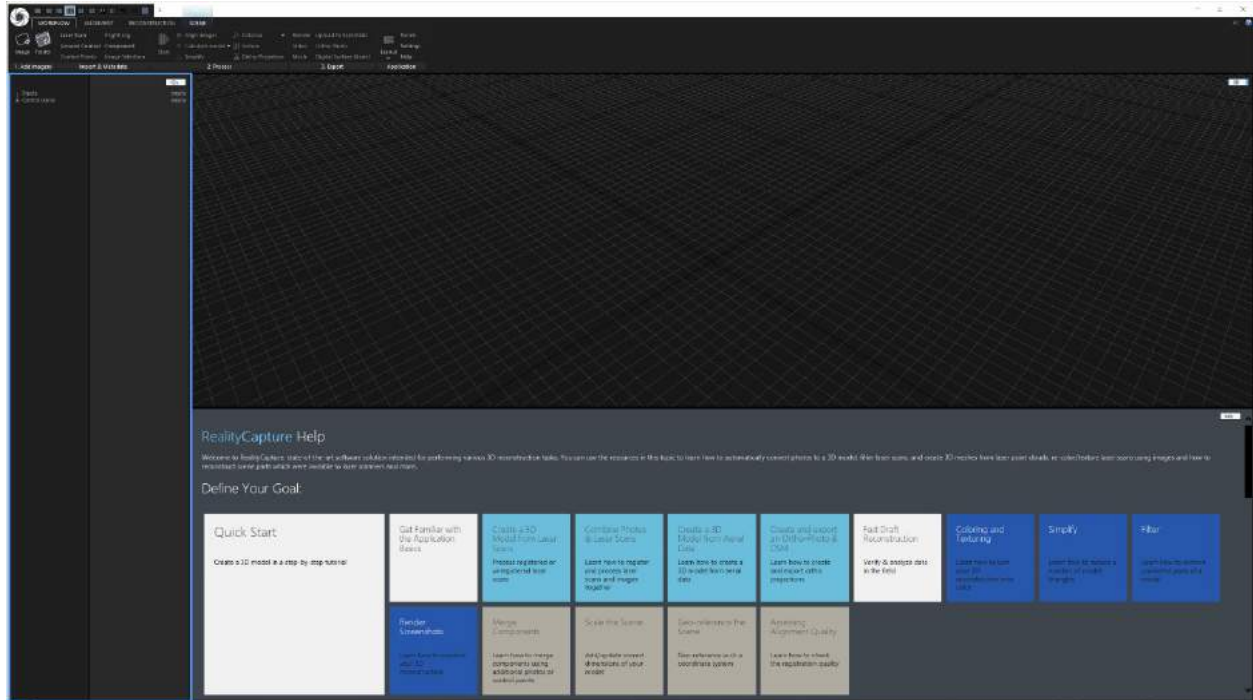


Figure 3-17. User interface of RealityCapture by Capturing Reality.

RealityCapture (Figure 3-17) was released to the public in 2016. It is considered to be one of the fastest proprietary photogrammetry applications currently on the market.¹⁶ It is among one of the most user-friendly paid software packages available for photogrammetry, with the ability to simply import your data and click a start button. It is generally recognized as one of the faster workflows; models often take less time to process in this program than with other applications. RealityCapture includes a draft mode to enable quick in-field visual inspections of the recorded data. The program can also incorporate laser scan with files captured from digital cameras.”¹⁷

16 Sean Higgins, “RealityCapture: Photogrammetry software built for speed (and laser scans),” Software, Spar3D, accessed April, 6, 2019, <https://www.spar3d.com/news/software/realitycapture-photogrammetry-software-built-for-speed-and-laser-scans/>

17 “What is the Computer Requirements?,” Reality Capture Support, Capturing Reality, accessed April, 6, 2019, <https://www.capturingreality.com/Product>

Cost¹⁸		
<p style="text-align: center;">RealityCapture Promo* (3-month license)</p> <p style="text-align: center;">\$110</p> <ul style="list-style-type: none"> • 3-month license • Free updates • Online during export ** • Max 2,500 images/ scans per project • No technical support <p><i>*Perfect for artists and freelancers</i></p>	<p style="text-align: center;">RealityCapture PGM* (Perpetual License)</p> <p style="text-align: center;">\$4,500*</p> <ul style="list-style-type: none"> • Perpetual license • 1st year free updates & technical support • 25% maintenance fee • No CLI possibility • No Laser Scans processing possibility • Max 2,500 images per project <p><i>*Optimal for photogrammetry projects</i></p>	<p style="text-align: center;">RealityCapture* (Perpetual License)</p> <p style="text-align: center;">\$16,800*</p> <ul style="list-style-type: none"> • Perpetual license • 1st year free updates • 1st year technical support • 25% maintenance fee • Offline during export*** • No CLI possibility <p><i>*Optimal for bigger projects</i></p>
<p style="text-align: center;">RealityCapture CLI (12-month license)</p> <p style="text-align: center;">\$8400*</p> <ul style="list-style-type: none"> • 1-year license • Fully-featured application • Command line Interface (CLI) • Free updates • Technical support • Offline during export*** <p><i>*For processing in batches</i></p>	<p style="text-align: center;">RealityCapture CLI (1-month license)</p> <p style="text-align: center;">\$840*</p> <ul style="list-style-type: none"> • 1-Month License • Fully featured application • Command line Interface (CLI) • Free updates • Technical support • Offline during export*** <p><i>*For processing in batches</i></p>	<p style="text-align: center;">RealityCapture CLI (3-month license)</p> <p style="text-align: center;">\$2100*</p> <ul style="list-style-type: none"> • 3-Months License • Fully featured application • Command line Interface (CLI) • Free updates • Technical support • Offline during export*** <p><i>*For processing in batches</i></p>
<p style="text-align: center;">RealityCapture CLI (6-month license)</p> <p style="text-align: center;">\$4200</p> <ul style="list-style-type: none"> • 6-months license • Fully-featured application • Command line Interface (CLI) • Free updates • Technical support • Offline during export*** <p><i>*For processing in batches</i></p>		
<p><i>* The prices displayed here may not be the final prices and an additional TAX may apply.</i></p> <p><i>** You can use the application offline without limitations. The app sends a small batch with statistics like the count of images, scans or triangles only when exporting results.</i></p>		

18 "Buy," Online Store, Agisoft, accessed March, 31, 2019, <https://www.agisoft.com/buy/online-store/>. Prices converted from Euro to USD (rounded to the nearest dollar???) on May 03, 2019.

System Requirements¹⁹	
Turntable Photogrammetry	Large-Scale Photogrammetry
<u>CPU:</u> Quad-Core Intel Core i7/i9	<u>CPU:</u> Server CPU (e.g. Intel Xeon)
<u>RAM:</u> 16-32GB of RAM	<u>RAM:</u> 64-128GB of RAM
<u>GPU:</u> GTX 1060, 1070, or 1080	<u>GPU:</u> One or more GPUs

¹⁹ "What is the Computer Requirements?," Reality Capture Support, Capturing Reality, accessed April, 6, 2019, <https://support.capturingreality.com/hc/en-us/community/posts/115000788731-What-is-the-computer-requirements->

ContextCapture by Bentley

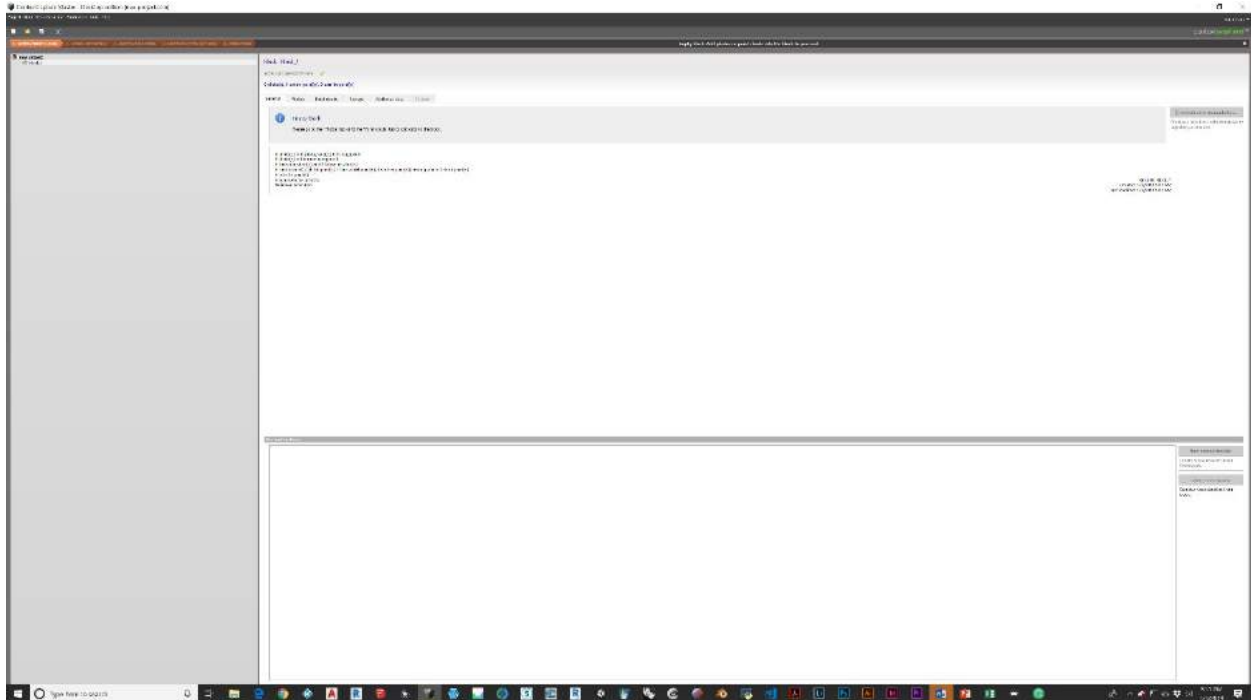


Figure 3-18. User interface of ContextCapture by Bentley

In 2015, Acute3D developed their photogrammetric program known as ContextCapture (Figure 2-18) and was promptly acquired by Bentley Systems, known for their architectural software suite.²⁰ The primary advantage of this program is that it aims to handle some of the most complex and large datasets being produced today. ContextCapture has the ability to handle up to 300 gigapixels of photos and/or up to 500 million points from a laser scanner. As with RealityCapture, this program can utilize hybrid datasets created from both digital photographs and laser scanning information.²¹

ContextCapture (as is the case with previous programs) can utilize data taken from multiple cameras and digital acquisition systems. It has many of the same capabilities of the other programs, plus a few other potentially time-saving and useful features: generation of animations, videos, and fly-throughs; it can create both 2D and 3D GIS models, as

²⁰ "Creating Accurate 3D Model from Photographs," GIS-Data, Spatial Source, modified November, 3, 2015, <https://www.spatialsource.com.au/gis-data/creating-accurate-3d-models-with-photographs>.

Ibid.

²¹ "Reality Modeling Software," Reality Modeling, Bentley Systems, accessed March, 31, 2019, <https://www.bentley.com/en/products/product-line/reality-modeling-software/contextcapture>.

well as generate CAD models, and other has further visualization options.²² In addition, Bentley has a service which they are calling ContextCapture Center, a cloud-based “grid computing” solution; by offloading the processing workload onto a server-based system such as this, model processing can be substantially expedited. The cloud-based service has costs associated with it, separate from the license for the modeling software.²³

Cost²⁴	
ContextCapture Master	ContextCapture Center
Owned: \$7,182*	One-time Charge: \$37,389*
Leased: \$1,005/ quarter	Leased: \$5,234/ quarter
<i>*Research and training licenses available at no cost as required.</i>	

System Requirements¹²		
Low Budget	Medium Budget	High Budget
<u>CPU:</u> Quad-Core Intel Core i7 CPU (e.g. i7-4770)	<u>CPU:</u> Octa-core Intel Core i7 CPU (e.g. i7-5820K +)	<u>CPU:</u> Octa-Core Intel Core i9 CPU (e.g. i9-9900K)
<u>RAM:</u> At least 32GB of RAM	<u>RAM:</u> 64GB of RAM	<u>RAM:</u> 128GB of RAM
<u>GPU:</u> Nvidia GeForce GTX 1060	<u>GPU:</u> Nvidia GeForce GTX 1080	<u>GPU:</u> Nvidia TITAN RTX

22 “Reality Modeling Software,” Reality Modeling.

23 “Creating Accurate 3D Model from Photographs,”.

24 Details provided via customer service representative over the phone (1-800-BENTLEY). Information accurate as of April 3, 2019.

25 “ContextCapture Hardware Recommendations,” Products, Bentley Communities, accessed March, 31, 2019, https://communities.bentley.com/products/3d_imaging_and_point_cloud_software/m/mediagallery/272490.

Meshroom by AliceVision

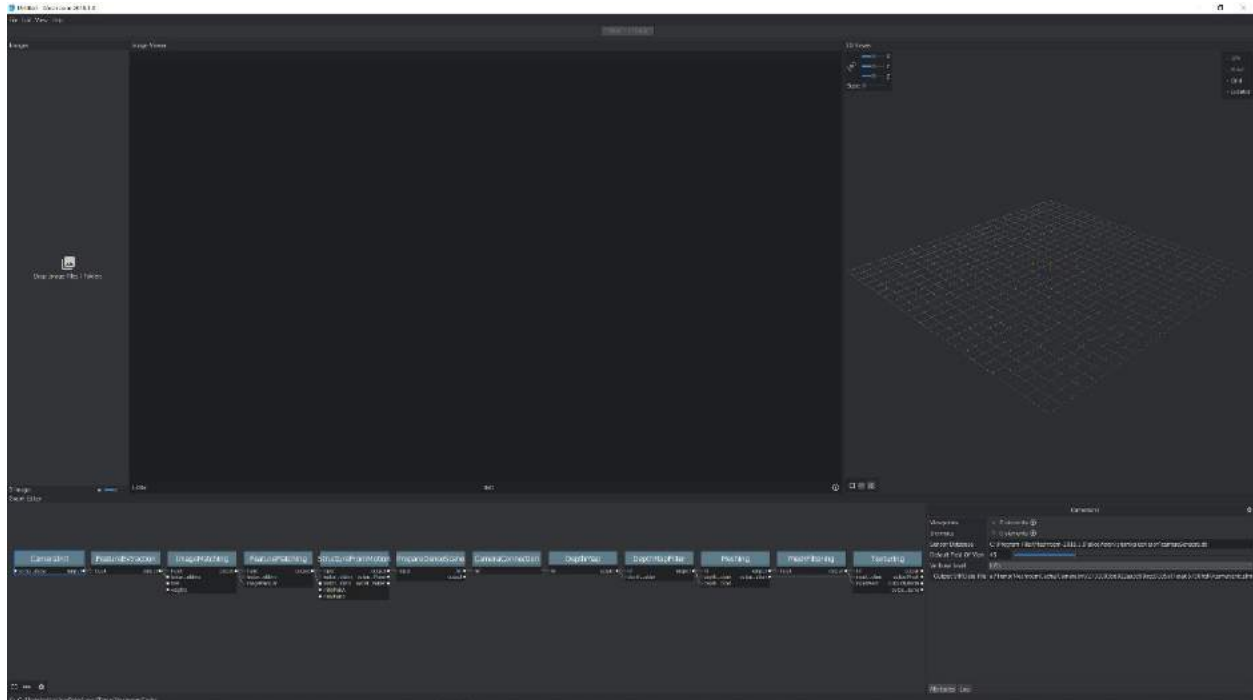


Figure 3-19. User interface of Meshroom by AliceVision

Meshroom is an open-source (meaning completely free) photogrammetry program (Figure 2-19). This history of this program’s development began in 2010 when the IMAGINE research team and Mikros Image partnered. They initially focused on supporting and developing the thesis work of Pierre Moulon. By 2013, this partnership resulted in the release of an open-source structure-from-motion (SfM) pipeline called open MVG (“Multiple View Geometry”). The team has continued to grow over the years, and developed a more, complete, customizable, all-in-one solution that has become Meshroom.²⁶

The fully automated photogrammetric pipeline that backs Meshroom is based on AliceVision, a photogrammetric computer vision framework. The AliceVision framework provides 3D reconstruction and camera tracking algorithms.²⁷ The Meshroom package

26 “Project History,” About, AliceVision, accessed April, 2, 2019, <https://alicevision.github.io/#about>.

27 AliceVision, *Meshroom Manual v0.4.4*, March 2019, https://docs.google.com/document/d/17HYtYS1tvx053k3_nO6Z2GnP2R3cXMIGMN-1Wle3kJE/edit#.

itself operates in a similar fashion to programs like Metashape or RealityCapture and has the same basic capabilities as well. These similarities and the fact that this is such a robust open-source (fee-free) option is why this program is being tested alongside the others.

Cost
<p>Meshroom</p> <p>FREE (Open Source)</p>

System Requirements²⁸	
Minimum Requirements	Recommended
<p><u>CPU:</u></p> <p>Not too old (~3 years and newer should be ok)</p>	<p><u>CPU:</u></p> <p>i7/Ryzen 7 or better</p>
<p><u>RAM:</u></p> <p>8GB+ of RAM</p>	<p><u>RAM:</u></p> <p>32+GB of RAM</p>
<p><u>GPU:</u></p> <p>Nvidia (or meshing can be done in draft mode if no GPU)</p>	<p><u>GPU:</u></p> <p>Nvidia GeForce GTX 1070+</p>

²⁸ "Project History," About, AliceVision.

SURE Aerial by nFrames

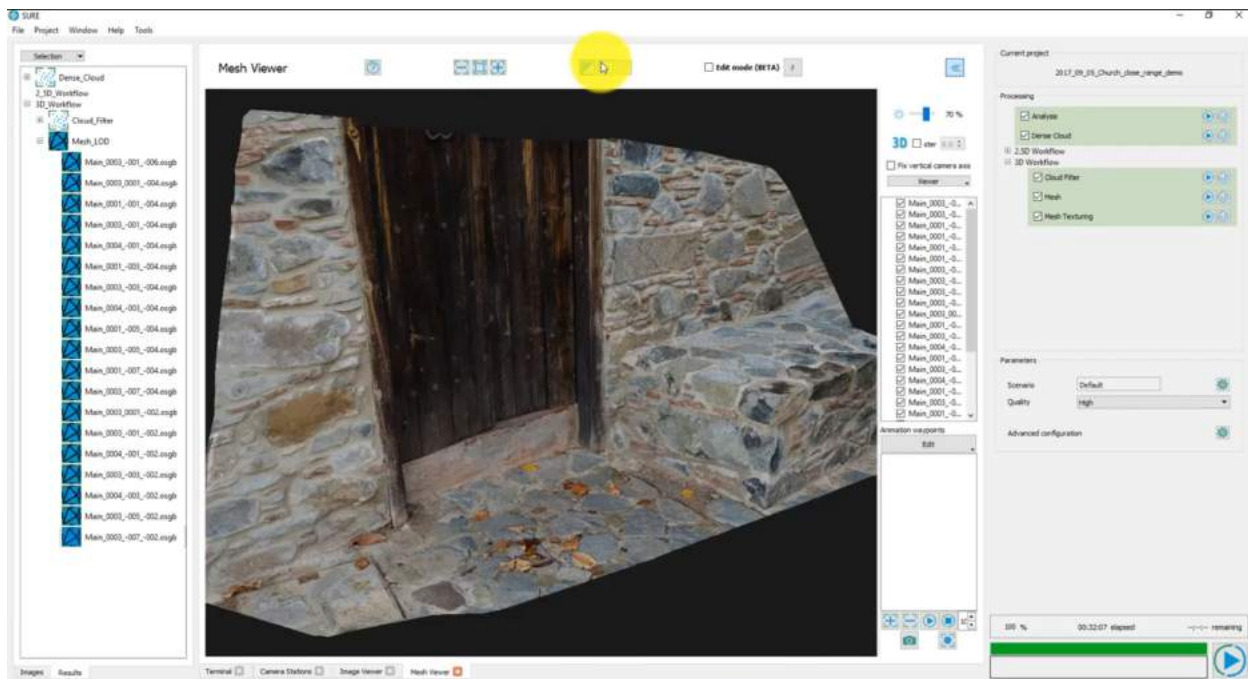


Figure 3-20. User interface of SURE Aerial by nFrames

Developed in 2012, SURE (Figure 2-20) is very different from the other four programs being evaluated. It is similar in the sense that the majority of its functions are automatic, but it requires the initial input of an image set with its orientation settings already established. A sparse point cloud must first be generated with a third-party program, through use of the SfM algorithm which aligns, rectifies, and orients the images.²⁹ In essence, SURE has the capacity to reconstruct and refine an already constructed point cloud and turn that into a fully textured 3D model.

SURE, like the other applications, is capable of handling multiple types of data captured from differing imaging sensors, and can be utilized for close-range, unmanned aerial vehicle (UAV, the technical term for a drone), and large frame aerial datasets. It is particularly efficient at handling extremely large datasets from images with very high resolution (e.g., >200 megapixels).³⁰ The product can be run on either the Windows or

²⁹ Mathias Roethermel and Konrad Wenzel, "Photogrammetric Surface Reconstruction from Imagery," Publications, Institute for Photogrammetry, accessed April, 3, 2019, <http://www.ifp.uni-stuttgart.de/publications/software/sure/index.en.html>.

³⁰ Ibid.

Linux operating systems, and takes advantage of computers with CPUs having up to 12 cores; distributed cloud-computing is also a possibility.³¹

Cost	
Research License	Standard Edition
Free 14-Day Trial	Call for a Quote
* or longer if allowed to expired and not used for commercial purposes.	

³¹ "SURE Pro," Products, nFrames, accessed April, 3, 2019, <https://www.nframes.com/products/sure-pro/>.

Minimum Requirements		Recommended Hardware
<p>SURE Pro (up to 60MP images)</p>	<p><u>CPU:</u> Intel i7/Xeon or AMD Threadripper/Epyc</p> <p><u>RAM:</u> < 1000 Images = 16GB > 1000 Images = 32GB > 5000 Images = 64GB</p> <p><u>GPU:</u> Optional</p>	<p><u>CPU:</u> Intel i7/Xeon or AMD Threadripper/Epyc</p> <p><u>RAM:</u> < 1000 Images = 16GB > 1000 Images = 64GB > 5000 Images = 128GB</p> <p><u>GPU:</u> Optional</p>
<p>SURE Aerial</p>	<p><u>CPU:</u> Intel i7/Xeon or AMD Threadripper/Epyc</p> <p><u>RAM:</u> < 5000 Images = 32GB (< 400MP – 2.5D only) < 10000 Images = 32GB (unlimited & full HD) < 60000 Images = 64GB (unlimited & full HD)</p> <p><u>GPU:</u> Optional</p>	<p><u>CPU:</u> Intel i7/Xeon or AMD Threadripper/Epyc</p> <p><u>RAM:</u> < 5000 Images = 64GB (< 400MP – 2.5D only) < 10000 Images = 128GB (unlimited & full HD) < 60000 Images = 128GB (unlimited & full HD)</p> <p><u>GPU:</u> Nvidia graphics card with compute capability 2.0 with >4GB and preferably >10GB of VRAM (e.g. GTX1080Ti, RTX2080Ti, etc)</p>

3.3 Standard Photogrammetric Workflow

Workflow Overview

With photogrammetry, there is a standard workflow that generally serves as a guideline for most project. Considerations should be made on a circumstantial basis with respect to these guidelines. Every project is unique and invariably requires some degree of subjective deviance. Photogrammetry does not mandate a one-size-fits-all approach. With experience, these deviations, if necessary, will become obvious. The following is an outline of the standard photogrammetric workflow as a general guideline only. Deviations specific to the research presented herein will be detailed on a case-by-case basis in Chapter 4, "Methodology & Case Studies."

Project Planning (Working in the Field)

Core Skills

Some fundamental skills are necessary to take advantage of photogrammetry. Basic photographic experience and familiarity with related equipment is a must, as is understanding how to use a camera to record a building or object. Being able to know the scope of one's work and degree of accuracy and detail required also helps. With practice, it's possible to know when photogrammetry is and is not preferable to other survey tools. It is also essential that one have experience with photogrammetric, graphic, and analytical software. Finally, of course, it helps to know how to interpret one's data for one's own needs and to have the ability to convey that information in a clear and visually appealing way.

Site Visits and Plans

It is always advisable to visit the project site as many times as possible to formulate a specific methodology and an appropriate photogrammetric plan. Taking a camera, of

any variety, along to create an image survey of the site and specific objects or building to be captured should be the first step to understanding your work environment. When such images are combined with field notes, the important aspects of a job will become evident. This will help to devise a plan for achieving project goals. In addition to field notes and image surveys, computer-aided drafting programs like AutoCAD can be utilized to produce site plans to diagram proposed camera locations.

Image Capture

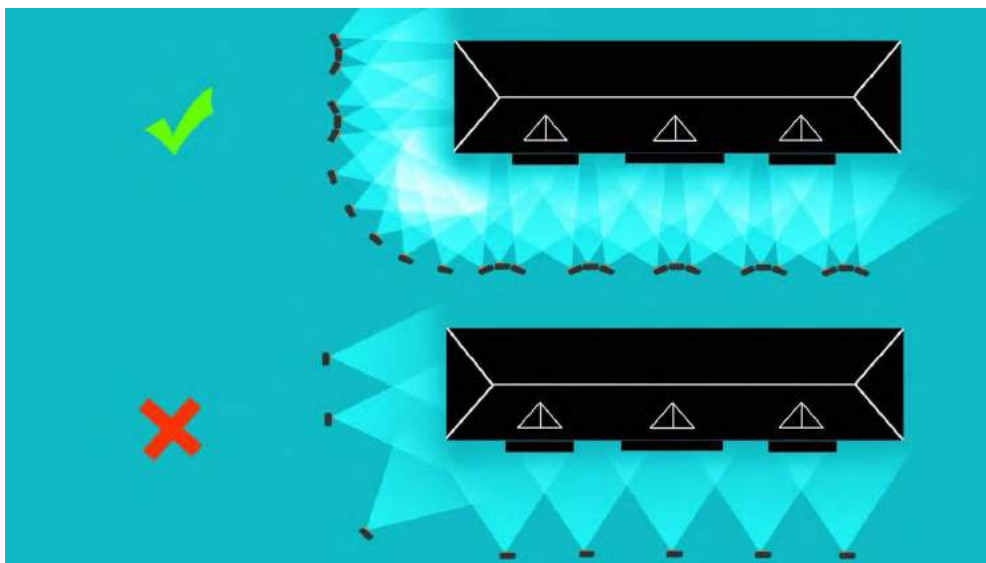


Figure 3-21. Proper method for orthographic architectural photography.



Figure 3-22. Photography at various heights makes it possible to record more information.

When it comes to the overall photogrammetric workflow, the way in which images are captured is critical. Particularly for architecture, there are certain methods by which

photographs should be taken. The graphics above demonstrate how to achieve the overlap mentioned previously. For the best coverage of an object or building, shots must not be taken only straight on, but at oblique angles too. It is also best to take them at varying distances and heights to record the greatest amount of data.



Figure 3-23. HABS crew using hybrid recording method of Yorktown Victory Monument, in Virginia.

In the above images, this principle is illustrated by the work of a Historic American Buildings Survey crew. This is the Yorktown Victory Monument, in Virginia. It is a tall structure and the crew is using multiple documentation methods to record it, including laser scanning. Laser scanning often provides more quickly attained accurate overall measurements, whereas photogrammetry is generally best reserved for hard-to-access areas, or areas with detailed ornamentation. Here, the crew is using a boom lift to take

their pictures of high detailed areas of the column and on the ground. From the ground, they are also using a pole to extend the reach of the camera to record the top of the monument's base.

Working with Your Data (Processing)

Prepping the Images

After all of the images are taken, they are processed by computer. One of the first steps is image pre-processing. This is where factors like exposure, white balance and color can be adjusted. The main software used is Adobe Lightroom (except in the case of handling the files taken with the Phase One which are read by another program, Capture One). Some open-source freeware may handle this format as well). The color chart noted previously was used to calibrate the cameras and to generate profiles that can be used in this editing process.

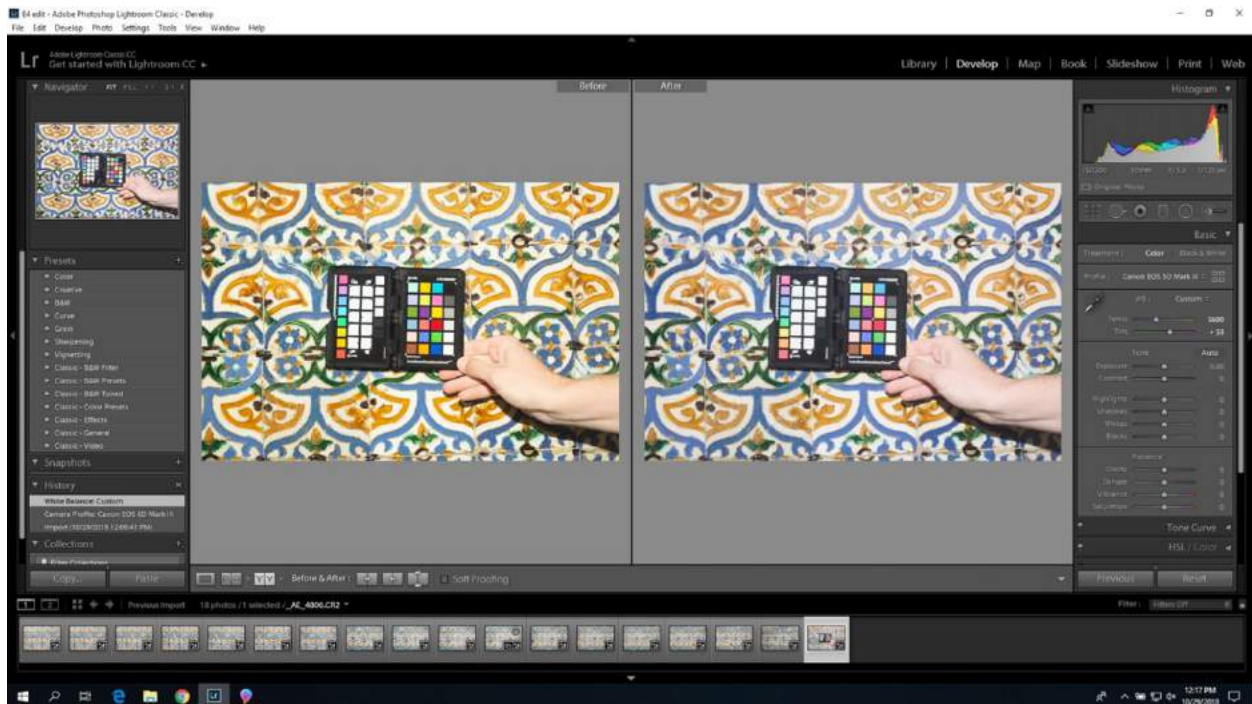


Figure 3-24. Adjusting white balance and color profile in Adobe Lightroom.

The above picture shows how the photograph on the right has been corrected. Features appear less yellow and more natural. The histogram located at the top right

of the application indicates whether or not the image is properly exposed, and whether one should correct for clipped highlights or shadows. It is always a good idea to slightly underexpose your images when in the field, due to the fact that digital images cannot reclaim lost or unrecorded highlight information.

Creating the Model

Every program used in this investigation has its own individual settings and workflow. Many of the fundamental processes remain the same. Below are the distinct general workflows for each program. These workflows were followed as closely as possible for the purposes of this project. Please refer to the individual manuals for further information to explain certain parameters that can be manipulated by the user. Manipulation of the default program settings is based on circumstantial project requirements. Examples of these types of adjustments specific to any of the experiments will be detailed in the following chapter.

Metashape by Agisoft

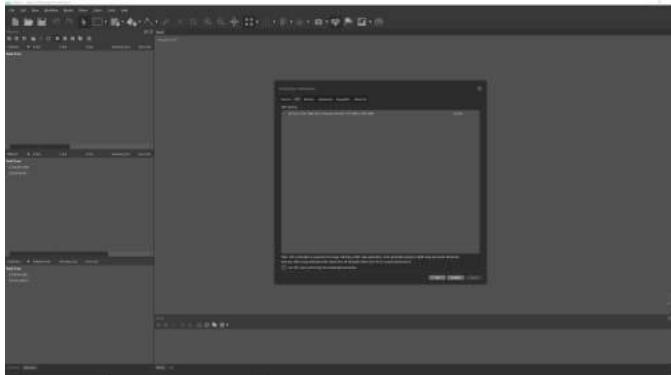


Figure 3-25. Preferences in Metashape.

Preferences

Before running any project, it is advisable to adjust program settings to one's specific needs.

The most important settings to check are under the GPU Tab. This is where one can enable processing with the graphics card if there is one.

(The Preferences dialog can be found under the General Tab under the Tools Menu.)

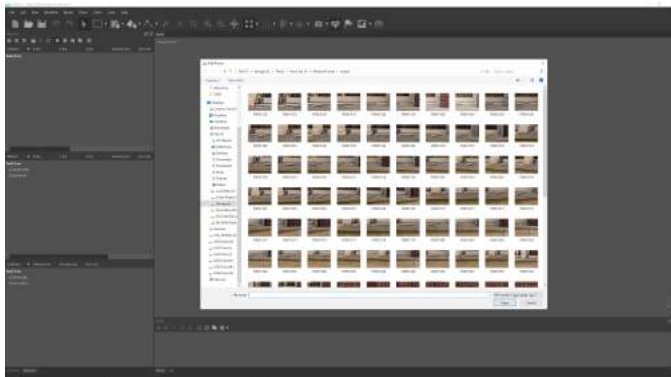


Figure 3-26. Loading photos in Metashape.

Loading Photos

After settings are adjusted, the program must be pointed to the directory which contains the photos.

To do this:

1. Select the Add Photos command from the Workflow menu.
2. Within the Add Dialog box, browse to the folder that contains the images. Once selected, click open.
3. The photos will now appear in the Workspace pane.

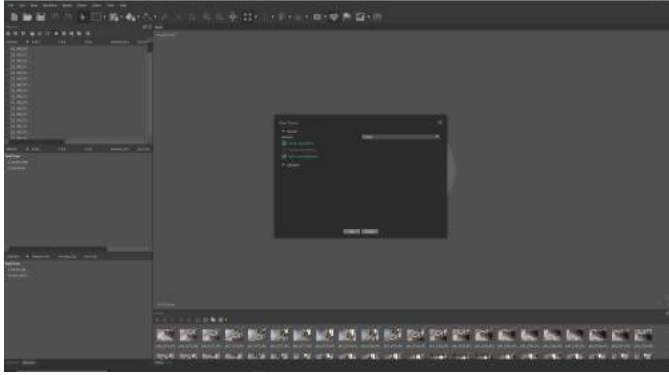


Figure 3-27. Aligning photos in Metashape.

Aligning Photos

After loading photos, Metashape aligns the images by determining the camera position and orientation for each photo, and then builds a sparse point cloud from that information.

Align photos by:

1. Selecting the Align Photos command from the Workflow menu.
2. In the Align Photos Dialog box, adjust the settings accordingly, based on specific project needs.
3. Click OK and wait for the alignment to finish generating the sparse point cloud.

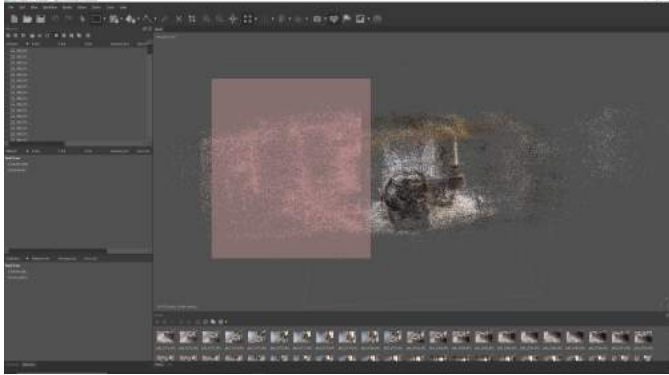


Figure 3-28. Editing point cloud in Metashape.

Edit Sparse Point Cloud

After the sparse point cloud is generated, it is often necessary to remove unwanted, extraneous points and account for points generated with large degrees of error.

There are a few editing tools for this purpose: Rectangle Selection, Circle Selection, Free-form Selection, and Gradual Selection.

1. It is advisable to use some combination of the Rectangle, Circle, and Free-form tools to remove obviously extraneous points first.
2. Then under the Model menu open the gradual selection pane.
3. Choose Reconstruction Uncertainty under Criterion. (The aim is to work your way towards a level setting of close to 10 without selecting more than 50% of the points each time this filter is run and you delete the selected points. It can be repeated as necessary. However, it is essential to run camera optimization after each filtration of points by selecting Optimize Cameras from the Tools menu, leaving the default settings in place
4. After you are satisfied with the results of that process, change the criterion to Projection Accuracy. (The aim this time is to achieve a level around 2-3, again without filtering out more than 50% of the points at any time. This step can also be repeated as necessary. Always continue to optimize cameras

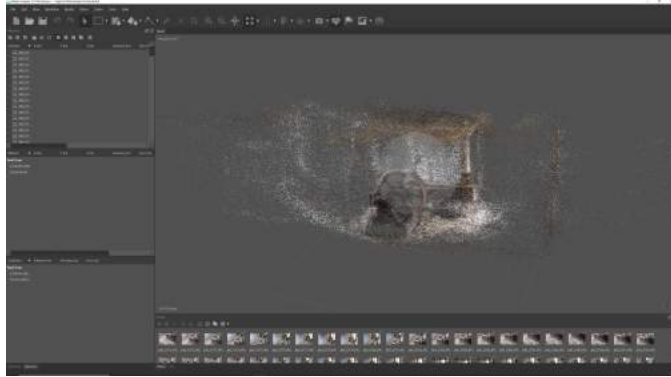


Figure 3-29. Building dense point cloud in Metashape.

Building Dense Point Cloud

The purpose of the dense point cloud is to repopulate the recently edited and refined sparse point cloud with more accurate information to aid in the model-generating steps which follow. The points generated from this process can often be similar in density to point clouds generated by other methods, such as LIDAR scanning.

To do this:

1. Arrange the reconstruction bounding box around the desired area of concentration. The tools for this are located on the main ribbon of the program.
2. After the Reconstruction Box has been satisfactorily oriented, select Build Dense Cloud from the Workflow menu.
3. In the Build Dense Cloud dialog box, adjust the parameters according to the project needs.
4. Click OK and the process will begin.



Figure 3-30. Building mesh in Metashape.

Building Mesh

From the information contained in the point cloud data, a polygonal mesh can be generated. The mesh is necessary for adding texture later and acts as a skin over the point cloud.

To build a mesh:

1. Being sure that the reconstruction bounding box is situated as needed, select the Build Mesh command from the Workflow menu.
2. Set the necessary parameters in the Build Mesh dialog box.
3. Click OK.

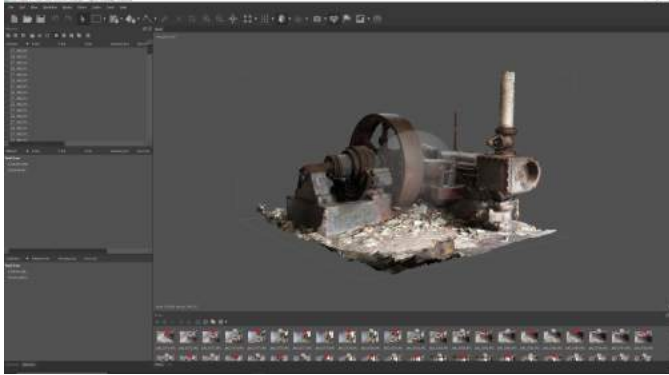


Figure 3-31. Building model texture in Metashape.

Building Model Texture

Once the mesh is complete, texture can be applied to the model.

To do this:

1. Select the Calibrate Colors option from the Tools menu. (This is only necessary if the lighting conditions changed dramatically over the course of image capture and if this hasn't been accounted for in previous photo processing prior to import.)
2. Select the Build Texture command from the Workflow menu.
3. In the Build Texture dialog box, select the texture parameters that are appropriate for the project.
4. Click OK.

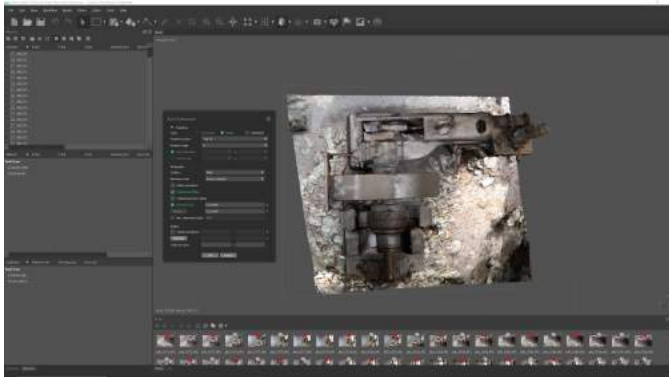


Figure 3-32. Building an orthomosaic in Metashape.

Building Orthomosaic

An orthomosaic (or orthophoto) is a useful output that can be generated from a 3D model. It allows for full and “idealized” perspective correction of parts of a model, such as building facades.

To do this:

1. Select Build Orthomosaic from the Workflow menu.
2. Set the parameters to reflect the type of image and resolution necessary. (Precise geographic coordinates can be applied here if they exist.)
3. Click OK.

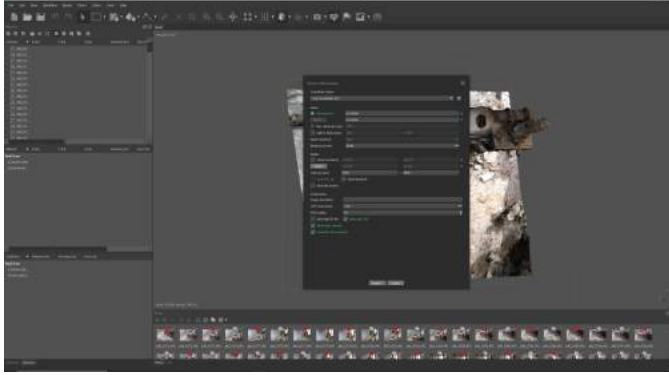


Figure 3-33. Exporting results in Metashape.

Exporting Results

Any and all types of file export can be done through the File Menu and selecting export followed by the type of export you desire (e.g. Point Cloud, Panorama, Orthomosaic, etc).

Reality Capture by Capturing Reality

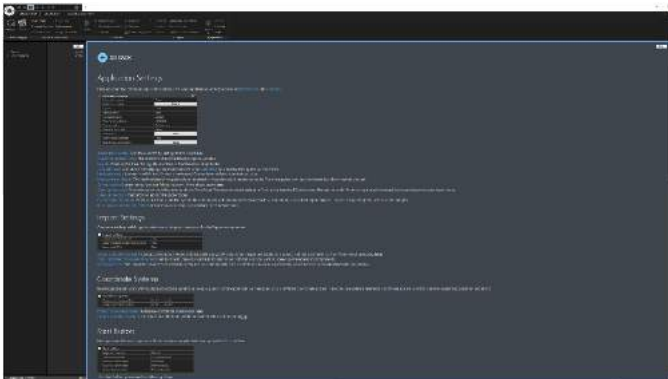


Figure 3-34. Adjusting settings in RealityCapture.

Settings

As in Metashape, one of the first steps in Reality Capture should be manipulating the settings of the project based on the desired output.

Reality Capture can be run as one complete process or in individual nodes or steps. There are settings which apply to either scenario.

For the purposes of this research and to ensure more control over the program, settings were tweaked for each individual step if/as needed.

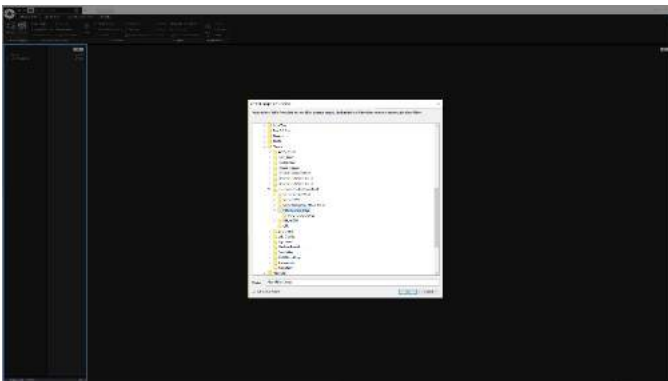


Figure 3-35. Importing photos into RealityCapture.

Importing Photos

After settings are adjusted, the program must be pointed to the directory which contains the photos.

This can be done a few different ways:

1. One can drag and drop images from a directory into the program or load them in individual selection or upload an entire folder of images all at once
2. Within the Add Dialog box, simply browse to the folder that contains the images. Once selected, click open.
3. The photos will now appear in the Workspace pane.

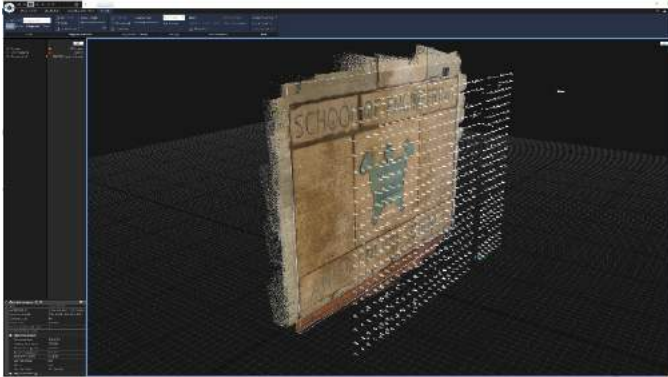


Figure 3-36. Alignment of photos in RealityCapture.

Alignment

After importing photos, Reality Capture, as with Metashape will complete the image alignment by determining the camera position and orientation for each photo and then building a single point cloud.

Align photos by:

1. Selecting the Align Images start button under the Alignment Tab or use keyboard shortcut F6.

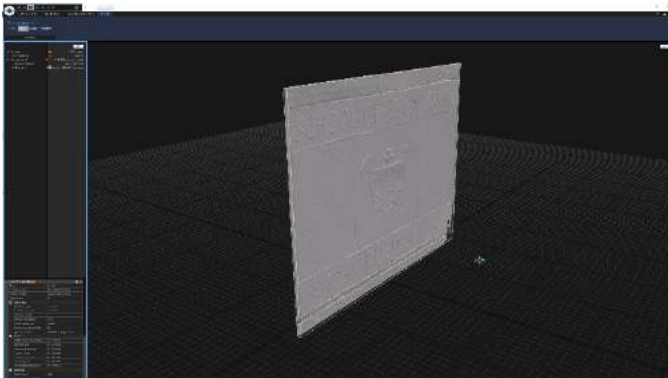


Figure 3-37. Reconstruction process in RealityCapture.

Reconstruction

The next node in the Reality Capture system pipeline is Reconstruction. After alignment, this is the last crucial phase of the processing. Reconstruction will enable the generation of a mesh from the point cloud created after Alignment. The options to colorize and texturize the mesh are also part of this phase. Some export options exist within this tab as well.

To Reconstruct:

5. Arrange the reconstruction bounding box around the desired area of concentration. The tools for this are located on the main ribbon of the program.
6. As with any other step in this program, additional settings can be accessed and manipulated based on particular project needs.

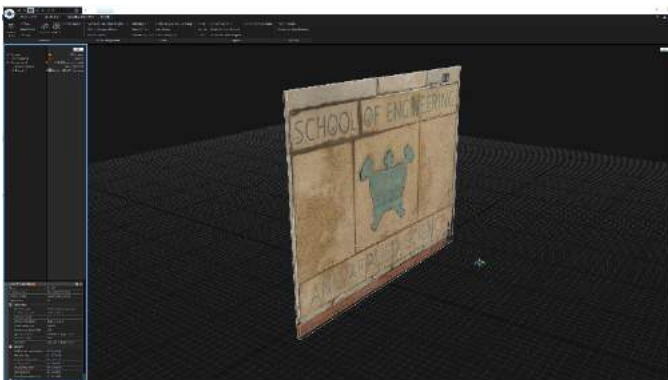


Figure 3-38. Texturing process in RealityCapture.

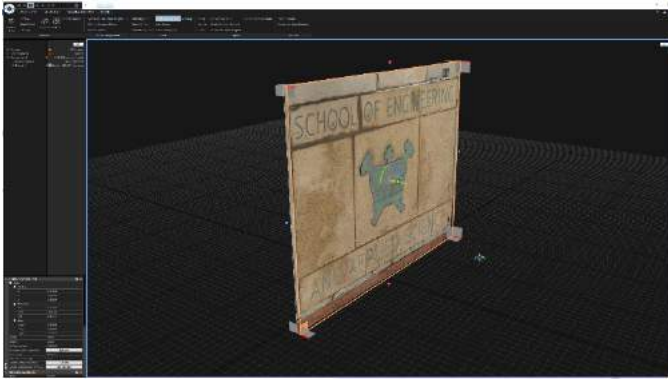


Figure 3-39. Rendering an orthographic projection in RealityCapture.

Render Orthographic Projection

**See explanation of “Building Orthomosaic” under the Metashape workflow for definition and further explanation of an orthophoto.*

To do this:

1. Select the Reconstruction tab in the ribbon and click on Ortho Projection (F10) in the tools panel.
2. Once the Ortho Projection widget appears, select the region of interest that corresponds to the area of interest.
3. Then, in the 1Ds view, settings for the ortho projection can be selected.
4. Click the render button after finalizing preferences.

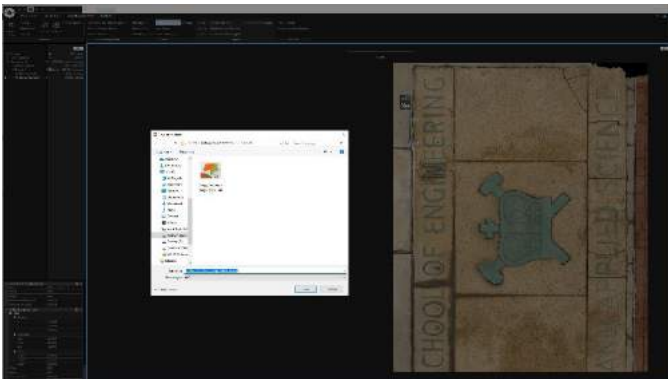


Figure 3-40. Exporting results in RealityCapture.

Exporting Results

Any and all types of file export can be done through either the Reconstruction tab or Scene tab (when 3Ds view is active).

From here, there are options to export files (e.g., mesh, renderings, fly-through videos, and orthophoto, etc).

ContextCapture by Bentley

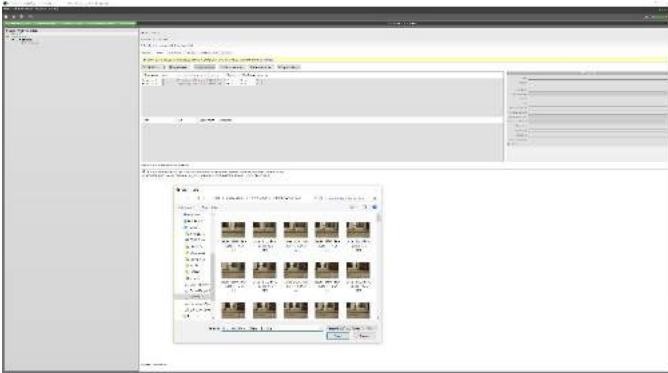


Figure 3-41. Inputting datasets into ContextCapture.

Input Photos/Video (or Point Clouds)

1. Under the Photos/Point Clouds menu, click on either the photos or point clouds tabs to import the relevant media. If information is missing regarding your camera sensor, it can be inputted manually here.
2. After this, click on submit "aerotriangulation".

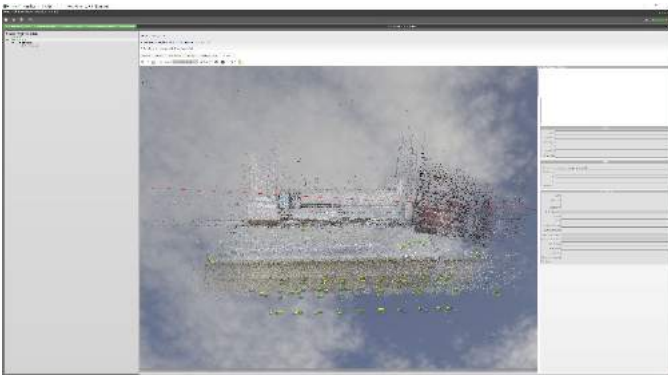


Figure 3-42. Aerotriangulation in ContextCapture.

Aerotriangulation

This step completes the photo alignment and produces a point cloud.)

1. After the photos have been successfully imported, one can (from the general tab) click on Submit Aerotriangulation.
2. Clicking through the dialog boxes, you can.

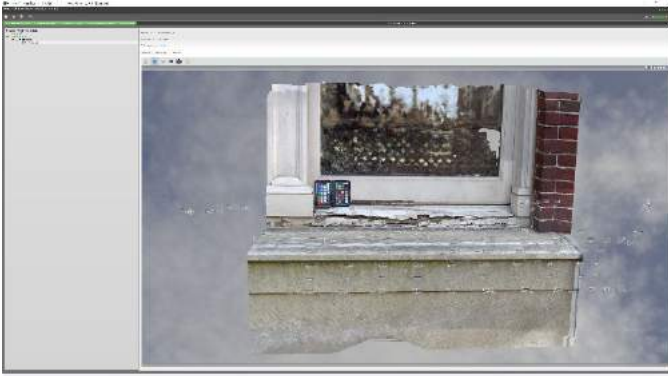


Figure 3-43. Reconstruction in ContextCapture.

Reconstruction

This is the last step in the digital model generating process.

To do this:

1. Select **Create New Reconstruction** from the general tab.
2. Then define the spatial reconstruction extents by manipulating the yellow bounding box.
3. Then click on **Submit a New Production**.
4. From the new dialog, enter the selected parameters.
5. Click **Submit**.



Figure 3-44. Generating outputs in ContextCapture.

Generate Outputs and Additional Editing

Generating additional outputs such as orthophotos, can be done one of two way, internally of with another application from Bentley, called Descartes. (This product is bundled with ContextCapture, but only if a perpetual license is purchased.)

Generate an orthophoto in ContextCapture:

1. On the lefthand side of the screen right click on the reconstruction of the block.
2. Attach the 3MX Reality Mesh file generated by ContextCapture.
3. Select Submit new reconstruction.
4. Click on Purpose.
5. Select Orthophoto/DSM and click next.
6. Enter the parameters.
7. Follow the prompts and click Submit.

Generate an orthophoto in Descartes:

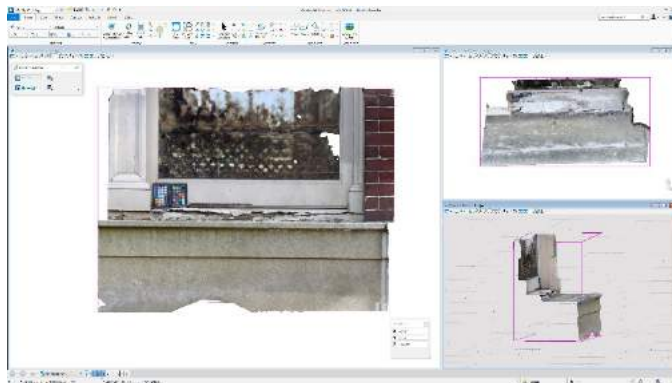


Figure 3-45. Generating an orthophoto in Descartes.

1. Open Bentley Descartes.
2. Attach the 3MX Reality Mesh file generated by ContextCapture.
3. Select the view you want to render (e.g., Top View for plans).
4. Use the merge tool in the Deliver tab to select the extents and export the orthophoto.

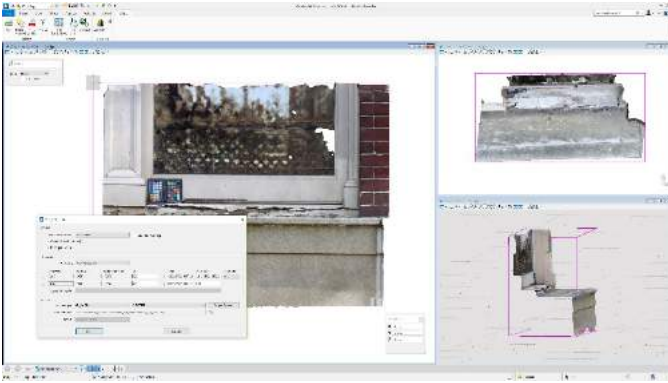


Figure 3-46. Creating sections in Descartes.

Creating Sections

Bentley Descartes has the ability to create sections from a model if the information recorded is dense and complete enough for this purpose.

To do this:

1. In the Home menu click on the Section tool.
2. Click on the desired starting point and then select an end point by moving the cursor in the preferred direction of the section and then selecting an end point. (The arrow indicates the View of the section.)
3. In the Deliver tab, click Merge.
4. Define the export area.
5. Select your options for file format, choose the preferred location, and then click on Save.

Meshroom by AliceVision



Figure 3-47. The default nodal pipeline in Meshroom.

Customizable Nodal Pipeline

Meshroom uniquely uses a nodal arrangement to customize the exact workflow of photogrammetric processing for specific needs. Once the nodes are in place one can then click Start and allow the software to do all the work.

Outputs are automatically exported into the chosen project directory and are ready to import into any additional program for visualization and editing.

The default, nodes are setup as follows:

1. Alignment Phase
 - a. Camera Initialization
 - b. Feature Extraction
 - c. Image Matching
 - d. Feature Matching
 - e. SfM
 - f. Prepare Dense Scene

2. Reconstruction Phase
 - a. Camera Connection
 - b. Depth Map
 - c. Depth Map Filter
 - d. Meshing
 - e. MeshFiltering

3. Texturing Phase
 - Texturing

4 Methodology & Case Studies

4.1 Methodology

Scope of Work

This study's main objective is a comparison of the viability of a variety of selected photogrammetric equipment packages to determine if, and to what extent, these setups represent practical options for architectural conservation. The investigation concentrates on a series of experiments designed to examine the correlation between factors such as the accessibility, usefulness, cost, and quality of the individual setups.¹

Conducted with several datasets produced by the various camera systems, four experiments formed the basis for this investigation. One experiment looked at architectural elements photographed indoors by each camera. Another, with data from all four camera systems, focused on an outdoor window sill on the Columbia University campus and was processed with four of the five photogrammetry applications (with only one dataset utilized as a control to compare results). The third and final experiment focused on a larger scale object, an entire building, The Dyckman Farmhouse in New York City. That experiment contrasted the time taken by the medium format camera to capture an entire structure to the time it would most likely take a terrestrial laser scanner to do the same.

Controlling Images & Datasets

For these results to be meaningful and as accurate as possible, it was necessary to try to maintain a certain degree of control throughout each experiment. Controlling the technical variables pertinent to the photogrammetric process was done in several

¹ For additional technical information about any of the equipment or software use, please refer back to Chapter 3 of this document.

ways. Not only were there several camera-related factors to be aware of while capturing the information, but utilization of the related photogrammetric equipment, and the manipulation of the data in the various programs, also played a role in the level of consistency, and had to be taken into account.

Natural Lighting & Weather

Lighting is sometimes one of the most challenging aspects of photogrammetry. Outdoors, the weather can change from hour to hour, and the sun can change positions rather quickly. Because of this, shadows may develop that are not favorable because “hotspots” can occur where the sun’s rays make things appear too bright and reflective. For this reason, the majority of image sets recorded were taken on partially cloudy to entirely overcast days, when the effects of the sun were less impactful. Of course, precipitation is a factor too; several winter storms and some rainy days limited the work on any given day or week. Planning around the weather meant that all camera systems did not capture some objects on the same day. On some occasions, they were captured weeks apart.

Lighting for interiors and objects captured indoors is an entirely different challenge and requires independent consideration. One might think just because something is indoors it is immune to the negative aspects of variable lighting. This premise could not be further from the truth. Daylight very much influences lighting indoors in rooms with windows. This concept is akin to what you might experience on a cloudy, rainy day. When it is dark outside, it always becomes darker inside, in the absence of adequate artificial lighting. When clouds pass in front of the sun, lighting changes too. Another issue when shooting indoors is the lighting in the rooms themselves. Every luminaire has a specific “color temperature” and therefore unique spectral distribution.

Artificial Lighting: Using a Dedicated Flash Unit

Because of the challenges of uncertain and uneven lighting conditions indoors, it is often advisable to use a dedicated flash unit. This practice was adopted when capturing architectural elements in the Preservation Technology Lab at Columbia University. Flash units excel at providing fill lighting. One must be careful when using a flash, however.

For example, a flash unit can produce a potent flood of light. If one is shooting an object with a glossy surface, such as glazed terra cotta or glass, lighting can generate strong reflections which can certainly introduce artifacts in a digital model, and may even prevent a program from being able to align all the images in a given image set. For this reason, a spherical light diffuser was used. It is merely a piece of translucent white plastic meant to be fitted directly over the end of a dedicated flash unit. This diffuser allows the light from the flash to be dispersed more evenly and naturally throughout space and not be focused directly at any one spot. A diffuser also prevents the color of a wall or ceiling from flooding the room and overtaking the appearance of the recorded image.

Camera Settings

One of the most reliable ways to maintain reasonable and assured photo consistency when capturing image sets for photogrammetry is by operating the camera in Manual Mode. Manual mode puts all of the essential functions of the camera in the control of the photographer (e.g., aperture, shutter speed, ISO, and exposure). Automatic settings are not recommended given that they can fluctuate with every image taken to a considerable degree.

Operating a camera in manual mode can seem to some a daunting task. Having an understanding of the meaning and relationship of the camera's settings is fundamental. What is required is considerable photography experience, and familiarity with the operation of many different types and models of cameras (including film-based systems to the latest digital models). Specific settings for each camera function must be maintained to expect useable and consistent photogrammetric data.

The aperture should be the first setting considered and selected. The aperture of a lens controls just how much of a scene appears in focus, otherwise referred to as depth of field. The wider the aperture (e.g., $f/1.4$ to $f/8$), the less depth of field, meaning just a very minimal area appears in focus. Smaller apertures ($f/11$ to $f/22$) present a greater sense of depth, meaning objects as near as inches to infinity can appear sharp and in focus. For photogrammetry, it is generally best to maintain a consistent aperture anywhere from $f/5.6$ to $f/8$. $f/8$ is generally a lens' "sweet spot" thus typically equaling the sharpest aperture for a given lens. For these experiments, however, $f/5.6$ was used. Using this setting means that in less than ideal or even darker lighting situations, the camera can gather in more ambient light and in shorter exposure times. Exposure time, of course, is directly proportional to the camera's shutter speed.

Shutter speed is the speed at which the camera's physical (or electronic) shutter mechanism opens and closes to record a photo. The camera's shutter is what makes the clicking noise heard when pressing the shutter release button. For best practice and to ensure reasonably-to-"tack-sharp" images, a good general rule is to ensure the shutter speed be set to at least $1/\text{focal length}$ when the camera is handheld. For a 35mm lens, an exposure time of $1/35\text{th}$ of a second. A slider or tripod assist in achieving sharp images without having to observe these rules.

ISO and Artificial Noise

ISO is the digital equivalent of film speed (termed ASA). This setting can be changed either higher or lower depending on the situation. The higher the ISO, the faster the resultant shutter speed. A higher ISO is most fitting for indoor photography, or for taking pictures at night. Increasing ISO, however, directly affects the amount of artificial image noise or digital artifacts introduced into an image. That is why a lower ISO setting is actually preferable in photogrammetry. Ideal ISO settings for photogrammetry are between 50 (or lower if applicable) and up to about 400. Beyond ISO 400, digital noise

presents a difficulty, and such noise is a discouraged source of digital bias. Trying to reduce the noise manually in post-processing will only negatively affect the digital model. Noise is artificial and therefore pollutes the digital model with erroneous and deceiving information. In these experiments, an ISO setting between 100 and 250 was maintained. My ISO settings fluctuated to some degree based on uncontrollable environmental conditions.

Exposure

Exposure is the last critical camera setting to monitor. Achieving perfect exposure is something that takes a great deal of practice, skill, and familiarity with a given camera system. When shooting, a light metering mode available on all dedicated camera systems, was used. The term for this method is spot metering. Spot metering uses the smallest degree of the center of the image sensor to pinpoint a particular object in a scene and to deliver an accurate exposure reading.

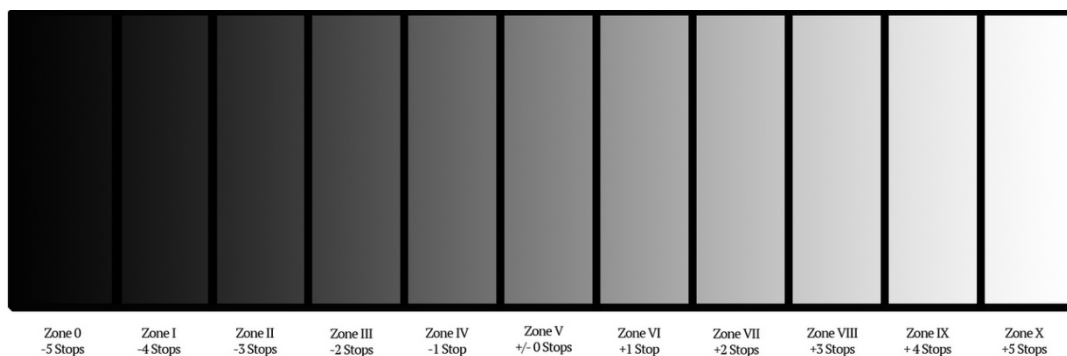


Figure 4-1. Illustration of the Zone System

The principles of the Ansel Adams Zone System were used, illustrated in the figure above (Figure 4-1). The Zone System divides exposure values up into ten stops, from dark to light. Adams used negative film when he was capturing images. With film, one always exposes for the important shadows in the image. In digital photography, one exposes for the highlights. Reclamation of overexposed, and thus unrecorded details, is not possible. The Zone System numbers each exposure stop with roman numerals., with (Zone 0 being pure black, Zone V (for example) denotes 18% gray, and Zone X to pure white). To ensure

proper exposure, in the experiments images were exposed with consideration for the most critical highlights in each scene. One should compensate for exposure by setting the camera's internal exposure level indicator up to Zone VII (or +2 stops above the center mark).

Focusing the Lens

There are two ways to focus a lens when taking pictures. Some lenses have the capability of autofocus. Autofocusing can be both a good and bad thing. It works adequately for objects that are far away, or when one needs to focus on something quickly. However, if using a lens with autofocus enabled, one must ensure sufficient calibration of the autofocus system to guarantee consistently sharp and accurate results. If not calibrated, a lens' autofocus system may function poorly, with an insufficient degree of precision. One might expect that the lens has focused on the subject when, in fact, it may have inadvertently focused either behind or in front of the intended target. Such occurrences are known as back-focusing and front-focusing. Calibration is the only solution to this potential issue. Autofocus is exceptional for wide angle context shots in photogrammetry. It was used when taking the more comprehensive contextual images for the experiments.

In some instances, lenses lack an autofocus function, or one might have a desire to use a lens without this feature. These lenses use a manual focus system. Manual focus means that the focusing is up to the photographer and not the camera. This may be desirable when one is capturing objects or elements of a building at a very close distance. Manual focusing is the technique that was employed on some of the close-range experiments done with the Nikon D850 and the Zeiss 85/1.4. Focussing a lens manually requires a high degree of precision and skill. Practicing before using this method is certainly advisable. Lacking familiarity with the method will slow one down in the field.

Image Pre-Processing: Color, White Balance, and Exposure

Adjusting images for color and white balance is something that not every photogrammetrist agrees is necessary. It is, however, just one more means by which to control the data. Some argue that this is not necessary because photogrammetry programs often can tweak these settings on their own; others more likely don't understand how to do it. To control images by adjusting for color the X-Rite ColorChecker Passport (a color chart) was used to create individual profiles for each of the cameras and lenses, so that the colors seen in the images represent standardized and uniform values. It is a matter of being as precise as one can.

The white balance of the images was corrected as well. This adjustment is often carried out after applying the color profile to the images in software such as Adobe Lightroom (what was used). The ColorChecker Passport was the tool providing control for these settings in this instance. These modifications were made with the Eyedropper tool in the Develop tab of Lightroom, selecting the 18% gray square on the color chart. Exposure is one more parameter that one can manipulate in image pre-processing.

Chromatic aberration (color fringing) is another parameter suitable for manual correction where it is apparent. Most of the lenses used in these experiments are optically exceptional and thus tend to exhibit little to no such abnormalities. Correcting any of these settings will not negatively effect data.

Scaling

Scaling is a necessary step when documenting heritage. It has application for any photogrammetric project, whether the work is oriented to archaeology, art, or, architecture. By controlling the scale of the project, one can accurately measure it. In these experiments, instead of the typical forensic scales seen in police reports, a machinist's rule was used, as it is accurate. This rule is so precise that all of the models achieved zero error in scaling. Another great feature of it is that it is high contrast and has low reflectivity, making it easy to read in post-processing.

4.2 Case Studies

Indoor Lab Experiment: Architectural Element

Experiment #1: Copper Finial



Figure 4-2. Copper Finial on turntable.



Figure 4-3. Copper Finial shown rotated 45 degrees.

The first case study in the experiment utilizes the copper finial pictured above (Figures 4-2 & 4-3), recorded in the Preservation Technology Lab at Columbia University. The finial was positioned on a turntable which allowed for consistent rotation. Photos were taken with each camera (Figure 4-4). The purpose of this study was to record the object with each camera system and compare the processed results using RealityCapture. Using one program allows for a level of control that can help mitigate the chances of introducing bias. RealityCapture was a strategic choice. It is one of the fastest programs available and results were thus outputted in a reasonable time-frame.



Figure 4-4. Equipment Setup for Capture of Copper Finial with Canon Camera

In the case of the iPad, there was no means to attach it to a tripod, and so it was handheld. The same hand-held method of capture was utilized for the Nikon and for medium format Phase One systems. This actually represents a more likely method for in-field use. In each instance, a camera flash was mounted to the hotshoe of the camera (except on the iPad which has no such functionality). As noted earlier flash allowed for more consistent lighting and faster shutter speeds, another means of control. As the Canon was mounted to a tripod for this experiment, the use of a tethered shutter release was possible. That tool limited any accidental vibrations or motion-induced blur that can occur in a handheld capture session.

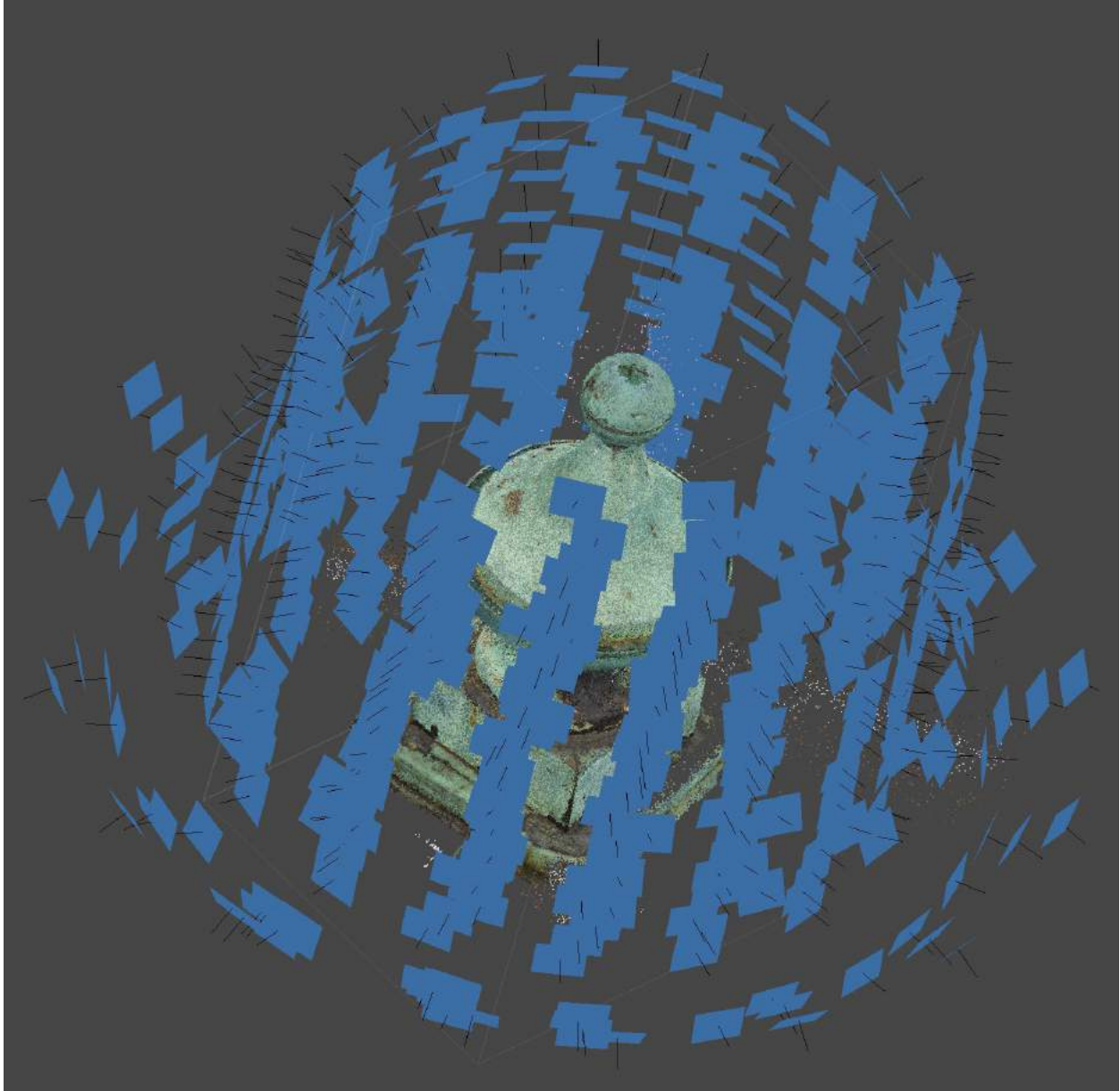


Figure 4-5. Each blue rectangle represents a camera position

Above is a screenshot (Figure 4-5) from Agisoft Metashape depicting the various camera locations for each individual image taken with the Canon camera, as the turntable was rotated. This screenshot also shows the resulting point cloud. With this many images in total, and the density of the point cloud shown, one might imagine that portrays a depiction of final textured model; instead, it is just a remarkably dense point cloud due to the high degree of image overlap and the total overall number of photos comprising the image set.

Outdoor Campus Experiments

Experiment #2: School of Engineering Emblem (Columbia University Campus)



Figure 4-6. Equipment Setup Used on School of Engineering Emblem

The School of Engineering emblem is located on a sidewalk on the Columbia campus, outside of the Mudd Building (Figure 4-6). The purpose of this particular experiment was to record an object with multiple materials and conditions, and, to test the equipment in a horizontal orientation. The program here is Reality Capture and the image on the following page (Figure 4-7) shows a dense point cloud that has been generated after aligning the several-hundred photos in each image set. The photo below portrays the locations of each camera during the capturing processes.

The weather interfered somewhat with this particular test. It took nearly four hours to record this object due to extremely windy conditions. These conditions induced strong shaking of the video slider upon which the cameras were mounted. (The manufacturer of

the stand provides heavier-duty models that would more likely be resistant to this issue.) Because of the wind, and also some restrictions in time with the cameras, this test was limited to the Canon and Nikon systems. Below is an illustration (Figure 4-7) of the various camera positions with the video slider.

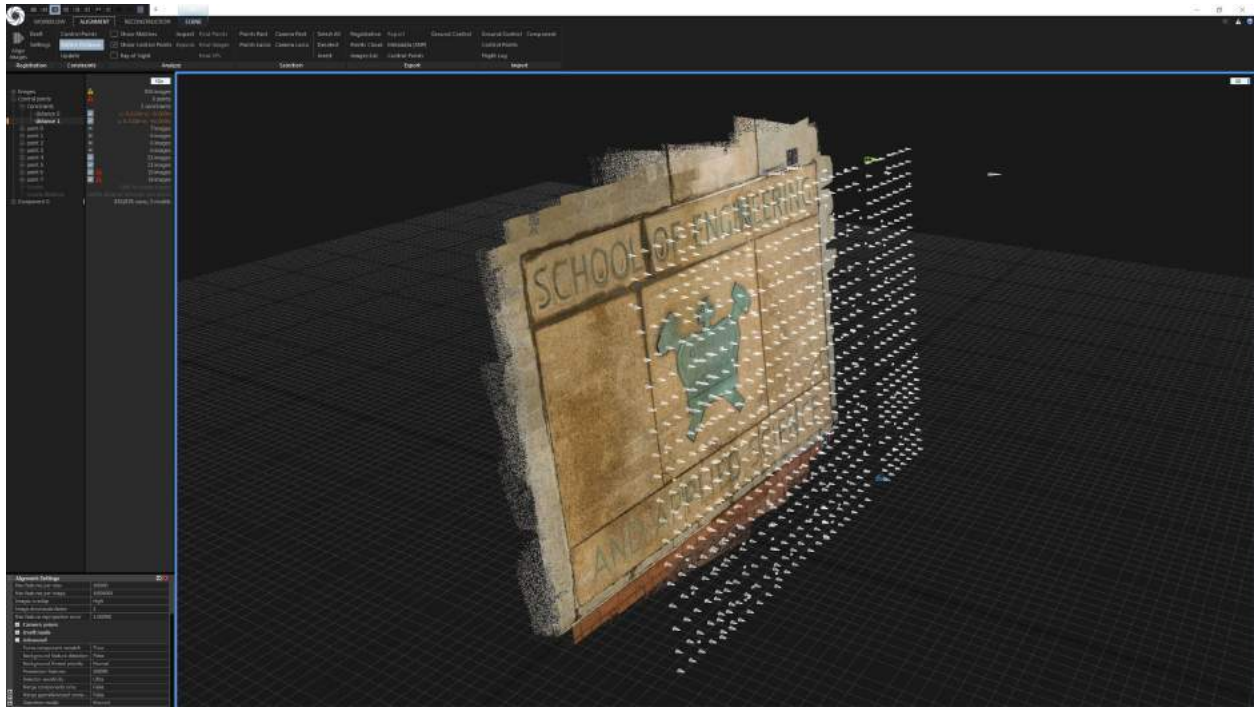


Figure 4-7. The white triangles in this image represent the many camera locations used to generate the point cloud.

Outdoor Campus Experiments (Continued)

Experiment #3: Window Sill (Avery Hall, Columbia University Campus)



Figure 4-8. The red arrow highlights the window studied in this experiment, located on the east elevation of Avery Hall.

This case study moves outside on the Columbia University campus to Avery Hall, focusing on a specific window sill on the east elevation (Figure 4-8). Here the slider was used to record a vertical surface. The purpose of this experiment was to compare images included in the Nikon D850 dataset after being processed through all five photogrammetry programs operated in this study. The illustration on the following page (Figure 4-10) shows the specific camera locations for each image as visualized by RealityCapture.

Only the Canon and Nikon camera systems were mounted to the video slider (Figure 9) due to restrictions of rental time-frames and the associated fees. This potential impact of this issue was addressed by relying solely on the Nikon dataset as a control.



Figure 4-9. Equipment setup for window sill experiment.

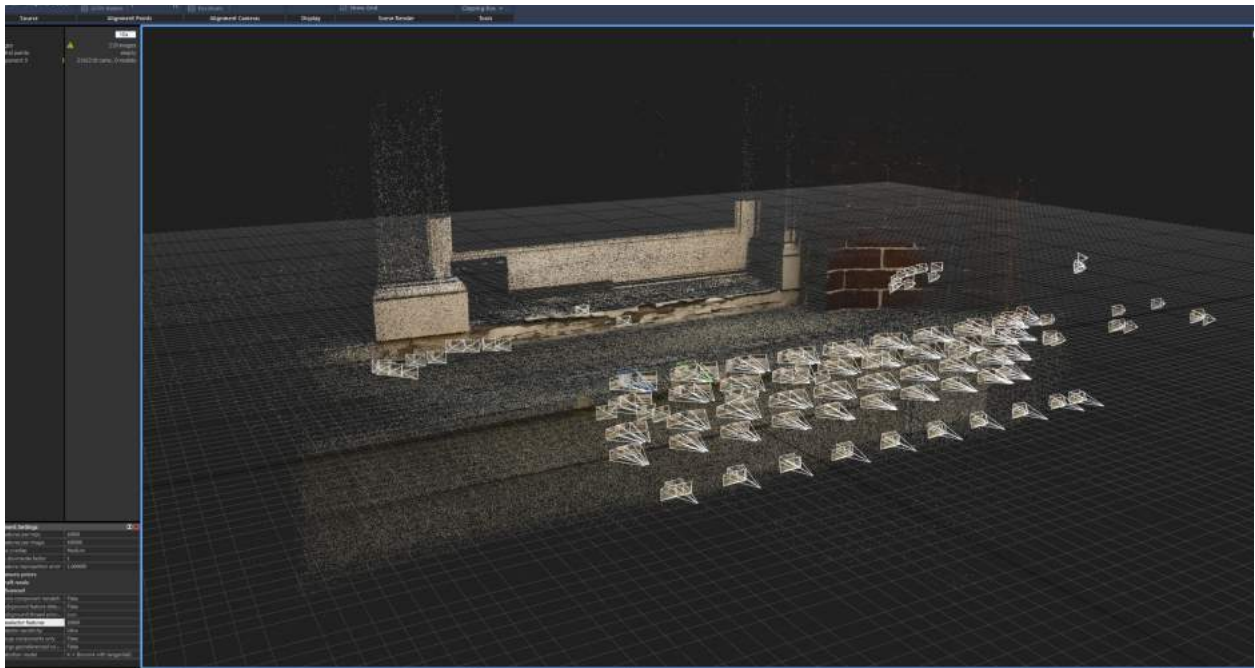


Figure 4-10. Camera positions for window sill experiment.

Off-Campus Experiment

Experiment #4: Dyckman Farmhouse (Inwood, Manhattan, New York City)



Figure 4-11. Dyckman Farmhouse (south elevation)

The final case study is the peculiar Dyckman Farmhouse (Figure 4-11), an 18th-century Dutch colonial building in Manhattan. A rare survivor surrounded by brick apartment buildings. The purpose of this study was to compare how fast the medium format camera could be used to capture and generate the digital model of an entire structure as compared to the time it might take for a terrestrial laser scanner to do the same. Having the largest sensor theoretically means that the medium format camera needs fewer pictures to be taken to capture the structure, in a short period of time. For a building of this scale, and with the various obstacles and challenges of the terrain, it would likely take a laser scanner, positioned in 15-20 different locations, and about 3-4 hours to record. The medium format camera captured the building in under 2 hours. Camera positions are shown on the following page (Figure 4-12).

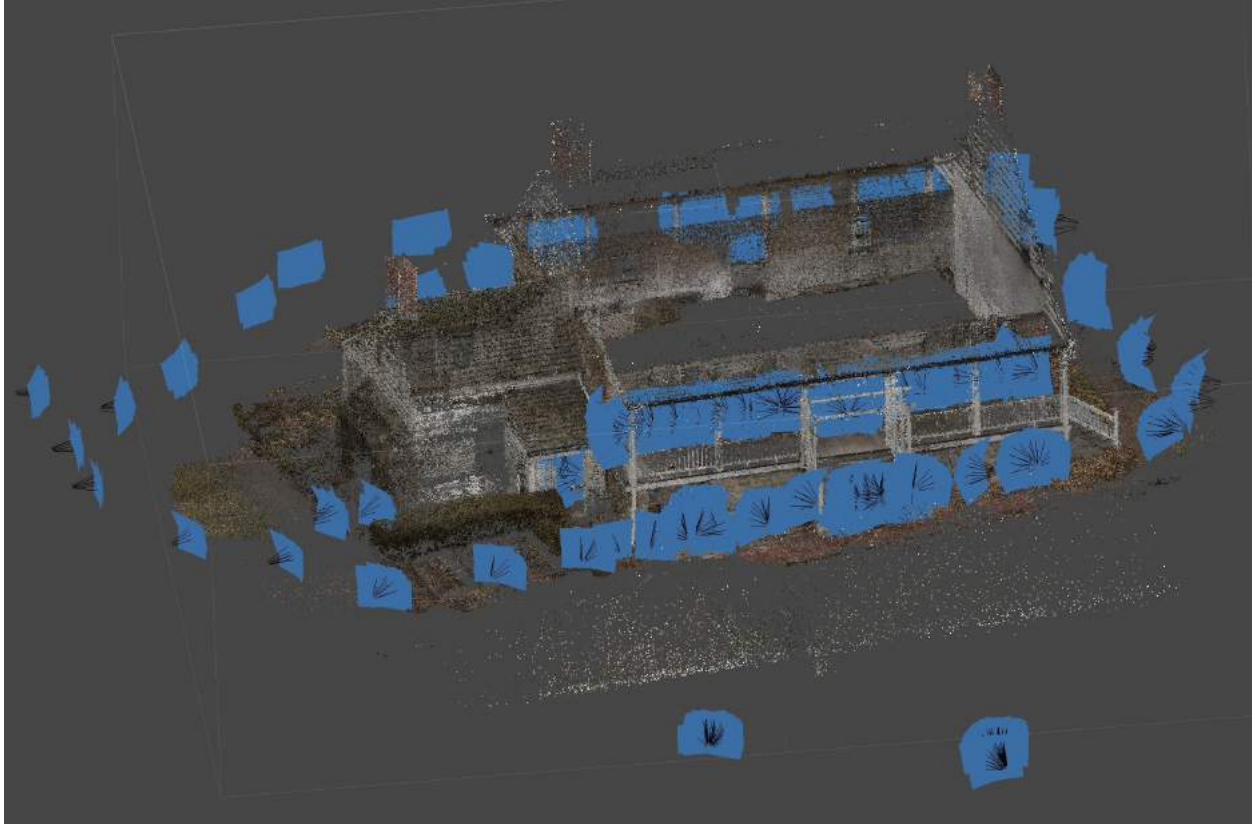


Figure 4-12. Point cloud and camera positions for Dyckman Farmhouse experiment.

5 Results & Analysis

5.1 Comparative Analysis Studies

Camera System Comparative Analysis

Methodology

One primary objective of this study was to observe and evaluate the differences in the output generated by the four camera systems: iPad Pro 10.5", Canon EOS 7D, Nikon D850, and a Phase One XF IQ4 150-megapixel system. To do this efficiently, consistently, and with as minimal influence possible, the digital models (one from each systems imagery) were processed using only one of the five photogrammetry applications, RealityCapture. The image sets from all four camera systems which captured the copper finial, as recorded in the Preservation Technology Lab at Columbia University, were chosen as the control data for this particular evaluation.

RealityCapture was selected as the control program for this experiment for several reasons: personal familiarity with the user interface and its many controllable parameters, the overall application speed; the current popularity of this new and rapidly accepted program; and the program's impressive ability to consistently and quickly align the majority of photos in a given image set.

The resulting digital models were analyzed through a myriad of analytical assessments. Comparisons were made by developing an evaluative matrix to record qualitative characteristics such as the digital models' visual results, (including obvious digital artifacts such as ghosting, and incorrectly attached mesh elements), and quantifiable resolution attribute differentials such as total points in a given model, processing time, surface density, and rugosity.

To measure the differences in the various forms of output produced by the data from each camera system, the implementation of a point cloud and mesh processing program known as CloudCompare was necessary. CloudCompare also functions as an analytical program; it excels at calculating discrepancies and other pertinent information specific to 3D data. In this instance, CloudCompare was used specifically to evaluate levels of point cloud surface density and rugosity of the digital models representative of the copper finial.

In a side-by-side comparative visual analysis (Figures 5-1, 5-2, 5-2, & 5-4), a rendering of the copper finial as generated by RealityCapture highlights several obvious differences. The models produced from cameras with larger sensors appear to have greater resolution; they are sharper, and minute details start to show. This difference narrows when comparing the models produced by the Nikon and Phase One imaging systems. The Phase One seems to be a bit less resolved than the smaller sensor Nikon. This could be due to a few factors: the Phase One camera is extremely heavy and is likely not meant to be handheld for any long duration. As such, the weight of the camera in hand while recording such a large dataset most likely resulted in some motion blur as it was difficult to hold the camera steady over the period of time it took to record the finial;. It is also possible that some of the images did not focus rapidly enough in the rather dimly lit lab, despite the use of a flash unit. One other apparent discrepancy between the four models is the difference in the blueish-green hue of the copper patina. It is slightly different from model to model. This is either because of the varying color temperature of the light in the room when the models were recorded or perhaps the way the automatic color correction settings were applied during reconstruction. All of the models retain surprisingly useful levels of information despite these variances.

Side-by-side Visual Comparison Study



Figure 5-1. iPad model.



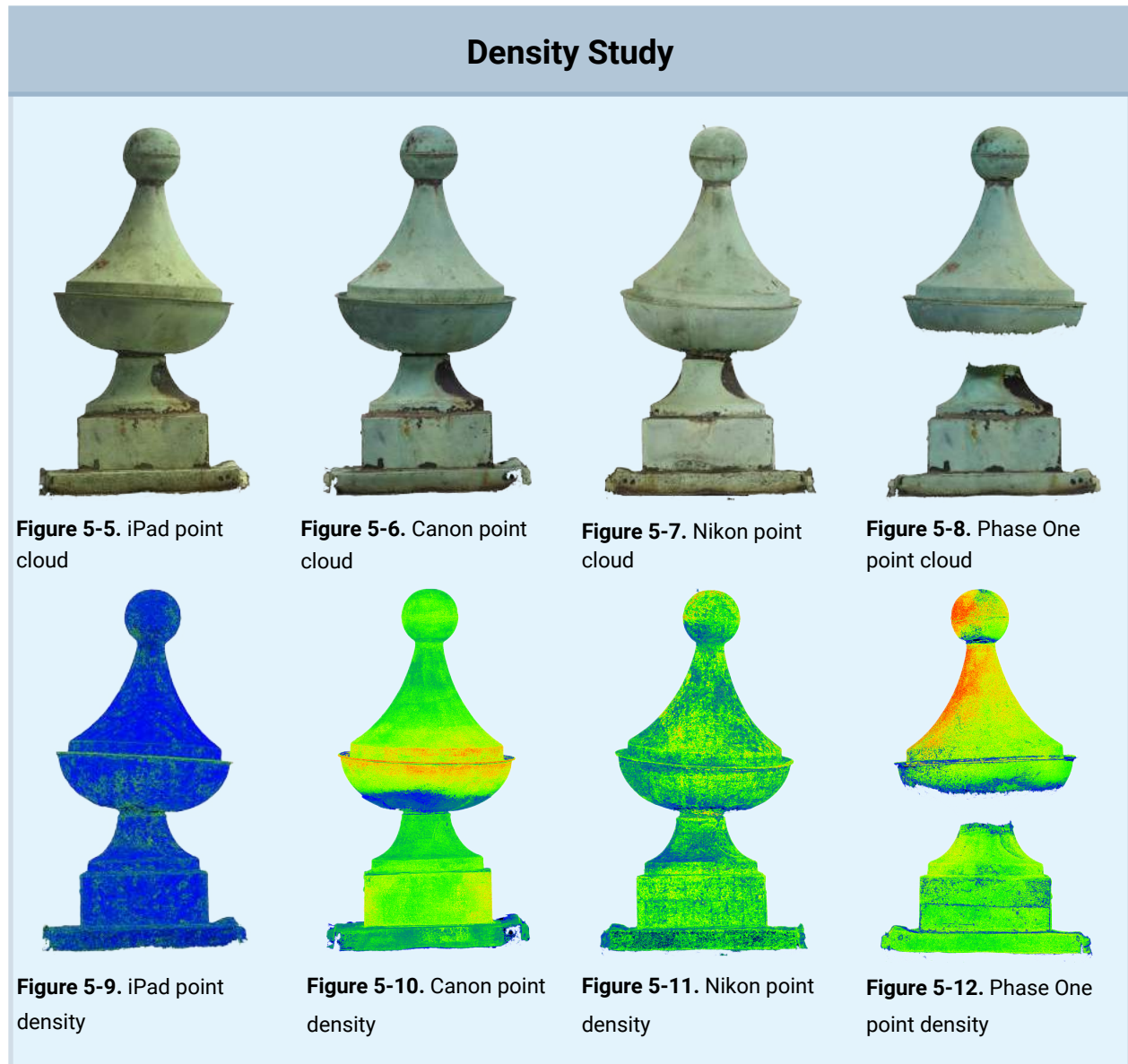
Figure 5-2. Canon model.



Figure 5-3. Nikon model.



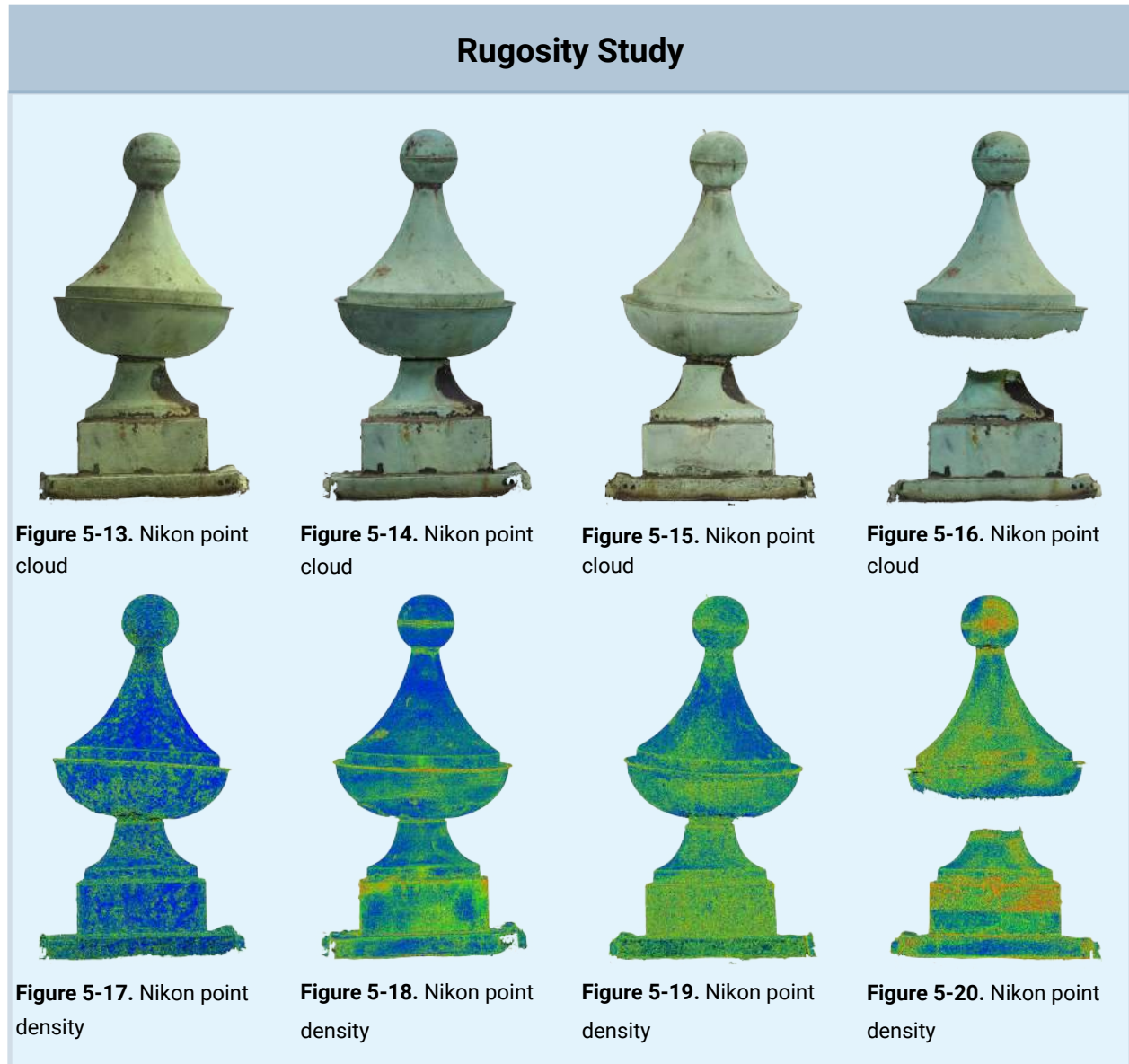
Figure 5-4. Phase One model.



Here the scalar values, illustrated as a color spectrum, spanning from blue to red, indicate levels of point cloud density from low to high, respectively. As one can see, the point cloud generated by the iPad image set (Figures 5-5 & 5-9) is far less dense compared to the Canon (Figures 5-6 & 5-10) and likewise, the point cloud of the Canon image set is far less dense when compared to the data produced by the Phase One system (Figures 5-8 & 5-12). However, when comparing the density of Nikon point cloud, it seems oddly out of place, being visibly less dense than the Canon point cloud. This can be attributed to the fact that the Canon model had nearly four times as many photos in its image set than the

Nikon model (Figures 5-7 & 5-11). The large number of photos is due to the camera being mounted on the tripod (while the other cameras were handheld) and had less overlap as a result. Typically, the denser the point cloud, the more information it contains. However, not all of that information is always quality data, as is demonstrated in the rugosity study. Perhaps even more interesting than that is the fact that the Nikon model is nearly as dense as the Canon, despite only comprising about a quarter of the number of images. Further, it is apparent that additional photographic overlap and a larger image set from cameras with smaller sensors results in higher resolution. All models produced here are remarkably feature-rich, meaning they are so densely packed with points that they nearly look photographic.

It is important to note out the missing middle section of the Phase One camera model. As time was extremely limited with that device (due to a narrow rental time-frame, made narrower still by a camera malfunction), that section of the object was simply not recorded. This is a perfect example of human error when working under pressure.



This set of CloudCompare screenshots illustrates rugosity, (more commonly called roughness). Roughness in this instance (as there is only one finial) can be interpreted to be an indicator of model detail and therefore quality. The point clouds with apparently the least amount of roughness (the most blue) are the least resolved, most likely having greater amounts of error and containing less detailed information. The point clouds that are seen as the most red are those exhibiting the greatest resolution and, in turn, the greatest quality. Therefore, from left to right, the point cloud resulting from the iPad (Figures 5-13 & 5-17) appears to be by far the smoothest (or blurry) and thus lacking in

detail; the Canon model (Figures 5-14 & 5-18) exhibits better quality than that, and the Phase One point cloud (Figures 5-16 & 5-20) is the sharpest, and containing the most detail of all three. For future work, it should be understood that rugosity for a new object is reflective of the method of fabrication. For an old exterior object, it is a function of the progress of weathering.

iPad Model of Copper Finial



Figure 5-21. iPad copper finial rendering.

Aligned / Total Images	148/151
Time to Capture	7 minutes
GSD Ground Sampling Distance "Potential Resolution"	0.022 cm/pixel
# of Points Generated	457,139
# of Triangles in Mesh	57.5 million
Total Processing Time	26 minutes
Unwanted Artifacts	ghosting, jagged edges, attached mesh artifacts
Point Cloud File Size	237 megabytes

Canon Model of Copper Finial



Figure 5-22. Canon copper finial rendering.

Aligned / Total Images	548/590
Time to Capture	26 minutes
GSD Ground Sampling Distance "Potential Resolution"	0.001 cm/pixel
# of Points Generated	2,097,554
# of Triangles in Mesh	249.5 million
Total Processing Time	12 hours and 18 minutes
Unwanted Artifacts	jagged edges, blur, holes, ghosting, mesh artifacts
Point Cloud File Size	4.28 gigabytes

Nikon Model of Copper Finial



Figure 5-23. Phase One copper finial rendering.

Aligned / Total Images	83/83
Time to Capture	12 minutes
GSD Ground Sampling Distance "Potential Resolution"	0.004 cm/pixel
# of Points Generated	181,144
# of Triangles in Mesh	14.2 million
Total Processing Time	1hr 38 minutes
Unwanted Artifacts	minor attached mesh artifacting, small holes in mesh
Point Cloud File Size	593 megabytes

Phase One Model of Copper Finial



Figure 5-24. Phase One copper finial rendering.

Aligned / Total Images	140/145
Time to Capture	8 minutes
GSD Ground Sampling Distance "Potential Resolution"	0.008 cm/pixel
# of Points Generated	984,083
# of Triangles in Mesh	174.2 million
Total Processing Time	9 hours
Unwanted Artifacts	Mesh artifacts where information was not recorded, small holes, and some minor jagged edges.
Point Cloud File Size	6.92 gigabytes

Experience with nFrame's SURE Aerial



Figure 5-25. Copper finial (model produced with SURE).



Figure 5-26. Background objects rendered in SURE.

The program SURE Aerial by nFrames was accessible via a 14-day trial. The licence to the program expired before thorough testing could be done on multiple elements studied in this project. However, a successful test was carried out on the copper finial in the Preservation Technology Lab. The complete reconstruction took only 48 minutes in total. This processing time puts the program at the center of the other four tested. Important to note is that SURE generates a model of the entire area captured as can be seen above (Figure 5-26). That makes the processing time all the more significant. The downside to the speed of this program is the obvious artifacting seen in the mesh reconstruction (Figure 5-25). An advantage, however, is the high level of detail in the model itself. This particular model was generated using the iPad.

Summary of Experiment #1



Figure 5-27. 600% Crop of iPad finial model.



Figure 5-28. 600% Crop of Canon finial model.

This is a comparison of renderings of the copper finial generated in RealityCapture. Clearly, the digital model captured by the iPad (Figure 5-27) has much less detail and even different coloration than the image on the right taken by the Canon camera (Figure 5-28). What is interesting here is that this particular Canon camera model is a decade, old and still manages to outperform the much newer technology of the iPad camera.

Another observation can be made about the differing color of the two models. This issue is concerning considering the level of scrutiny paid in ensuring color calibration of the camera and processed images imported into RealityCapture. The reasoning behind this is likely the result of several factors; First, these models were not captured on the same

day. Even though they were shot indoors, the room where they are kept has large windows and the change in natural lighting from outdoors clearly had an effect. Second, the iPad was not used with a flash unit as was done with the Canon. The flash unit ensured much more even lighting, and natural colors could be captured. Beyond that, it's possible that RealityCapture modeling process introduces subjectivity. The algorithms of the program produce, at best, an interpretation of the original object. The same can be said for any other photogrammetry application.. When the software processes the images it is highly likely that some type of color adjustment happens.



Figure 5-29. 600% Crop of iPad finial model.

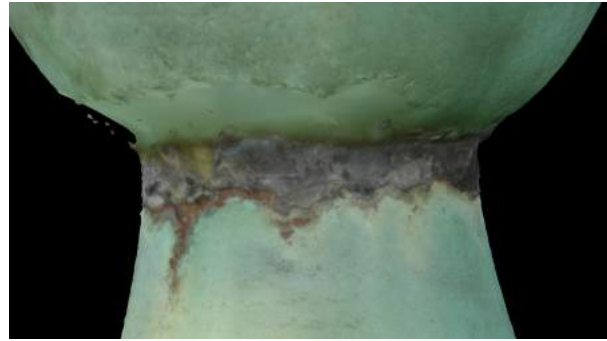


Figure 5-30. 600% Crop of iPad finial model.

Zooming in to 100% of the actual image size at the top portion, just below the ball at the top, of the finial affords an extreme comparative look at the results from the iPad (Figure 5-29) and the Phase One medium format camera (Figure 5-30). Clearly the medium format camera bests the iPad by a great deal in this evaluation. Not only does it retain far more detail, as evidenced in this focused view, but an overall visual analysis of the entire model showed that digital model contour lines produced by the Phase One are far more accurate and smooth compared to the rough and jagged lines seen in the iPad version.

Photogrammetric Model for Material Identification & Conditions Survey

Methodology

The primary goal of this particular study was to capture a horizontal architectural feature using the video slider to achieve a high level of overlap and photogrammetric precision. Recording outdoor horizontal surfaces provided an interesting opportunity to employ photogrammetry in a dynamic real-world setting. The School of Engineering emblem was subject to quickly changing natural lighting from the sun. The buildings surrounding the site only served to add an additional challenge as shadows set in around mid-morning.

The model was initially captured with two camera systems (Canon EOS 7D and Nikon D850) but for the best use of time, resources, and in the interest of producing a high quality model to record materials and conditions, the Nikon D850 was used in this instance. Again, RealityCapture was the software employed for this study. The resulting digital model was used to produce typical measured line drawings and conditions overlays, as might be done by an architect or architectural conservator.

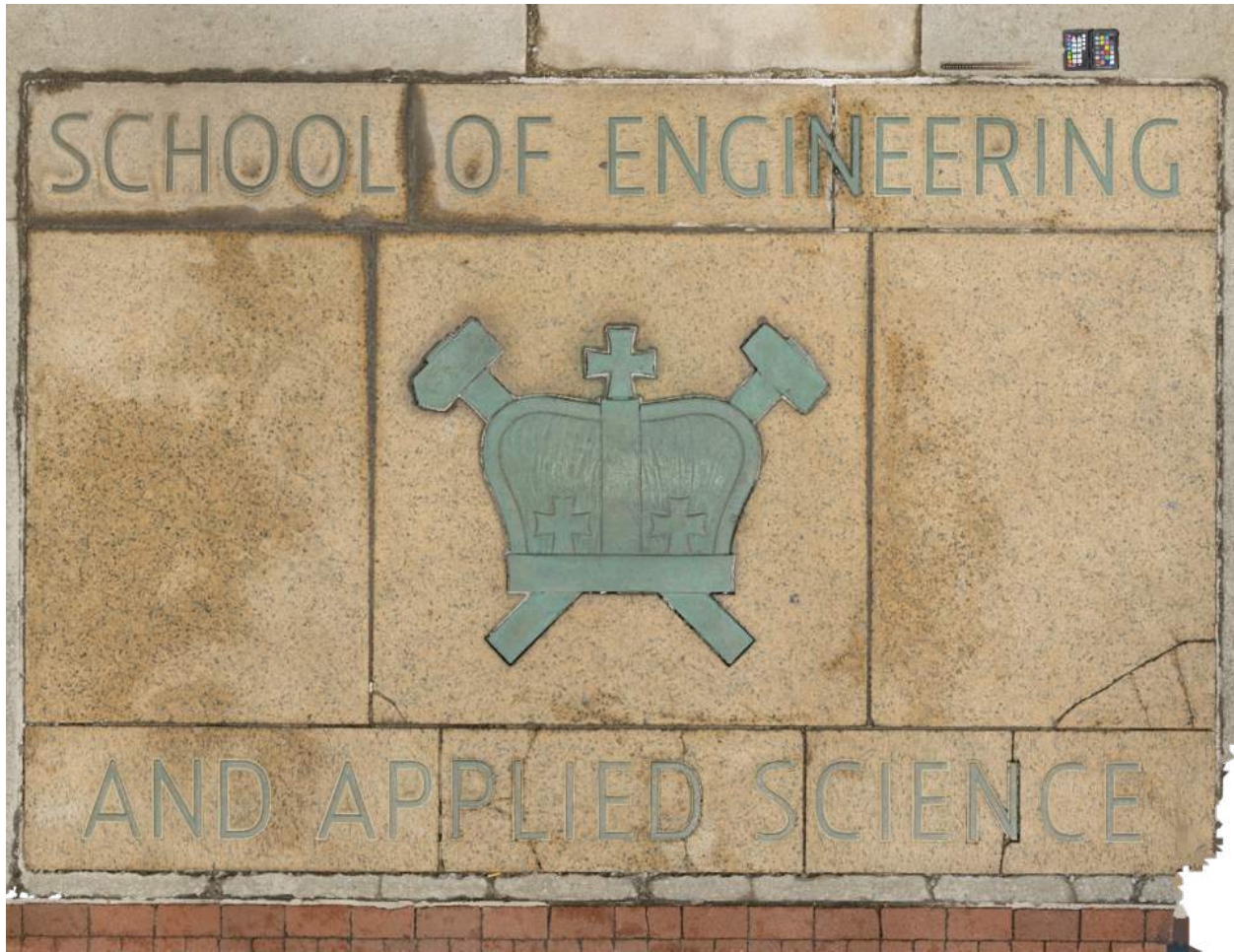


Figure 5-31. Orthographic image from 3D Model of School of Engineering emblem.

This is the orthographic photo of the School of Engineering emblem generated by the Nikon D850. It was used to create the drawings (Figures 5-32, 5-33, & 5-34, 5-35) on the following pages.

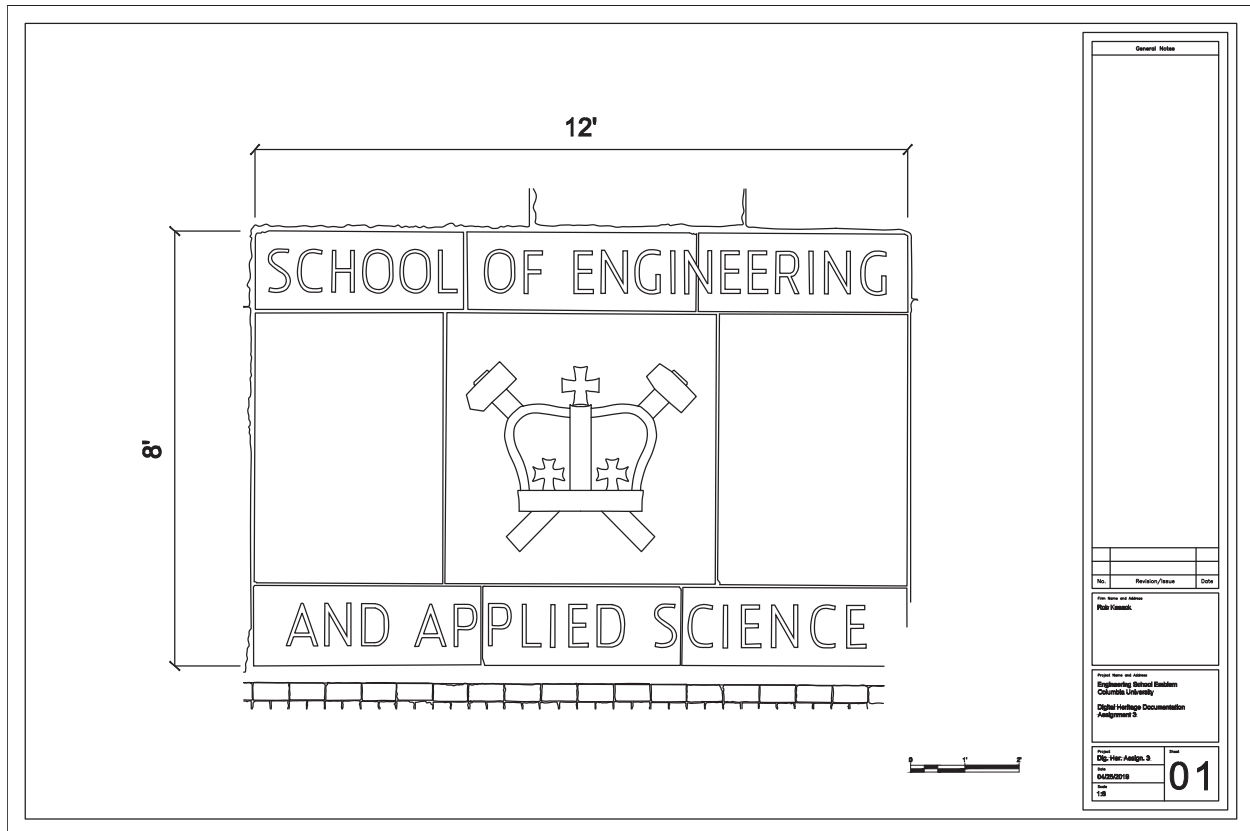


Figure 5-32. Orthographic image from 3D Model of School of Engineering emblem.

This is an example of a typical 2D measured architectural drawing that can be produced from photogrammetric models. This particular model was traced in AutoCAD over the orthographic photo on the last page (Figure 5-31).

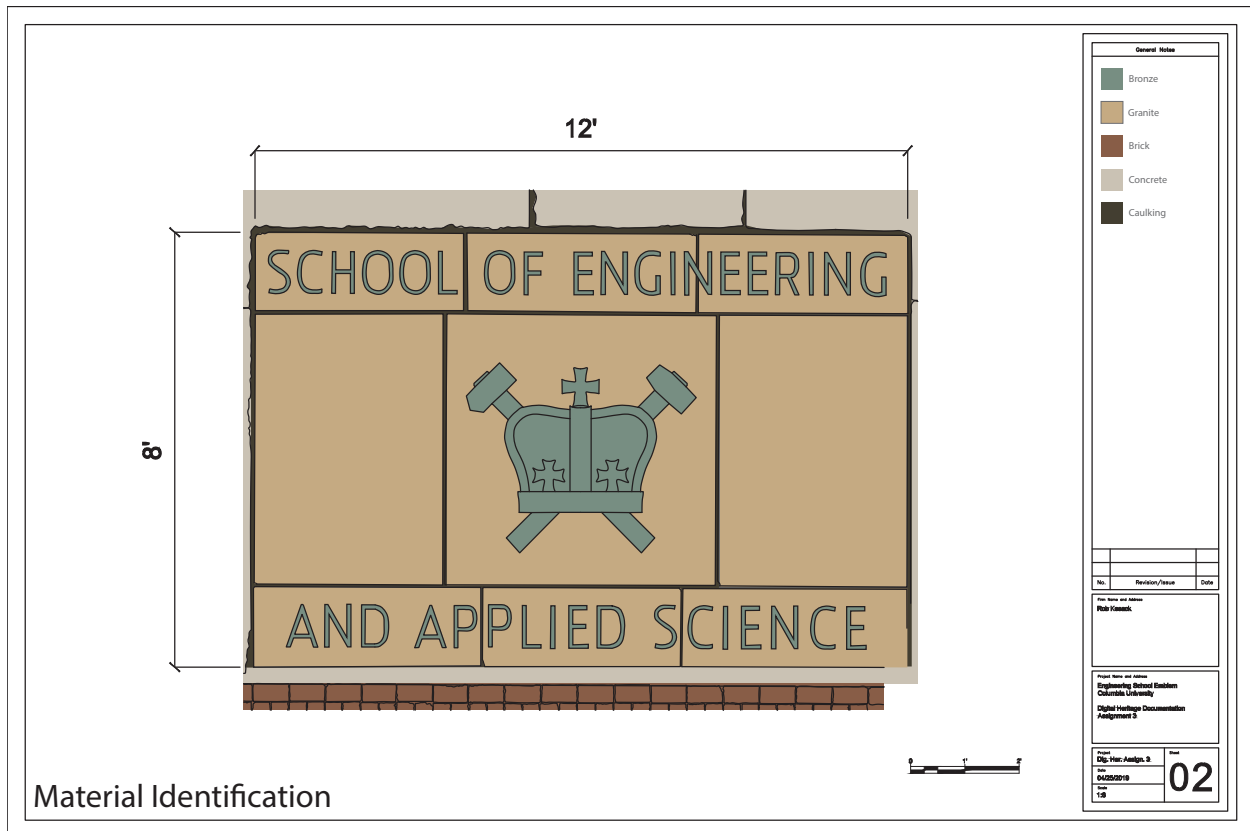


Figure 5-33. Material identification for School of Engineering emblem

Here (Figure 5-34) is a version created in Adobe Illustrator as traced over the orthographic photo of the School of Engineering emblem. This particular drawing portrays the materials that comprise the architectural element.

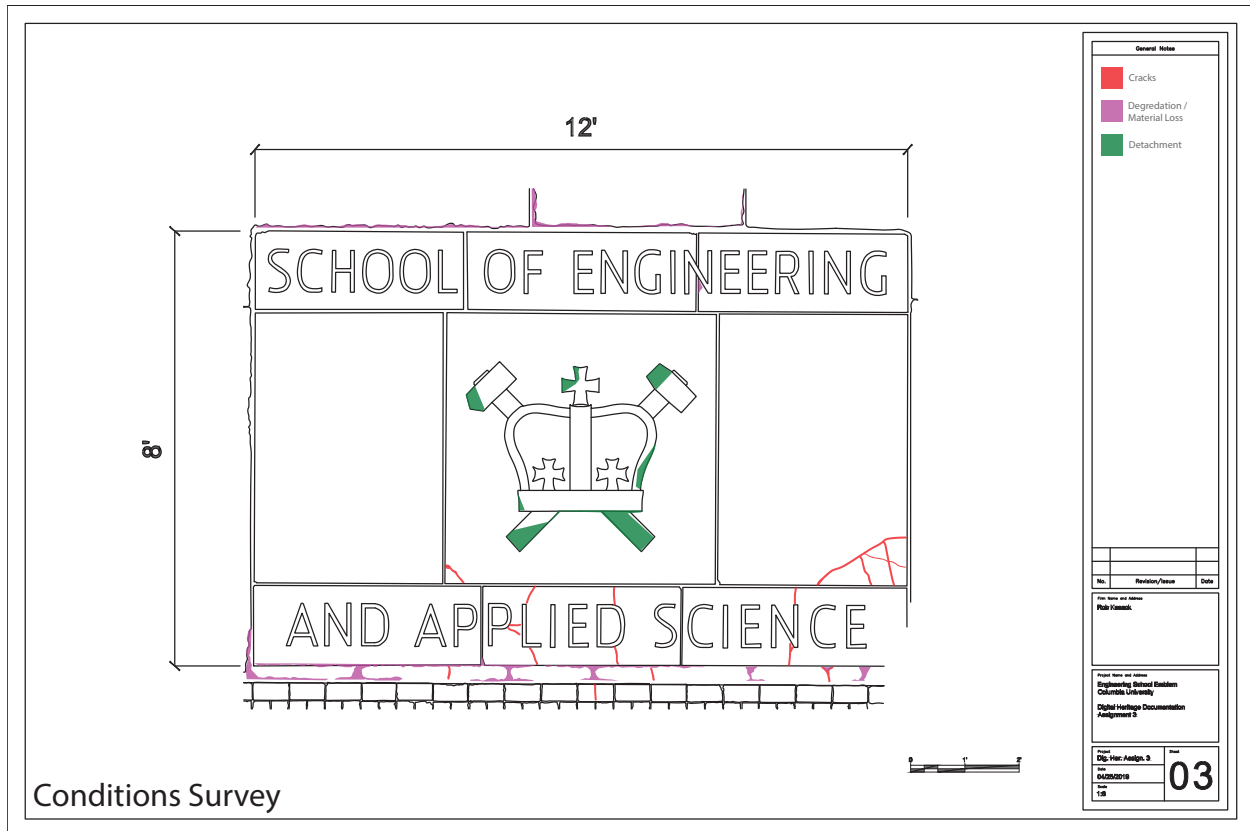


Figure 5-34. Material identification for School of Engineering emblem

The above image illustrates how the graphics of a conditions survey can be overlaid on top of a line drawing as created from photogrammetry.

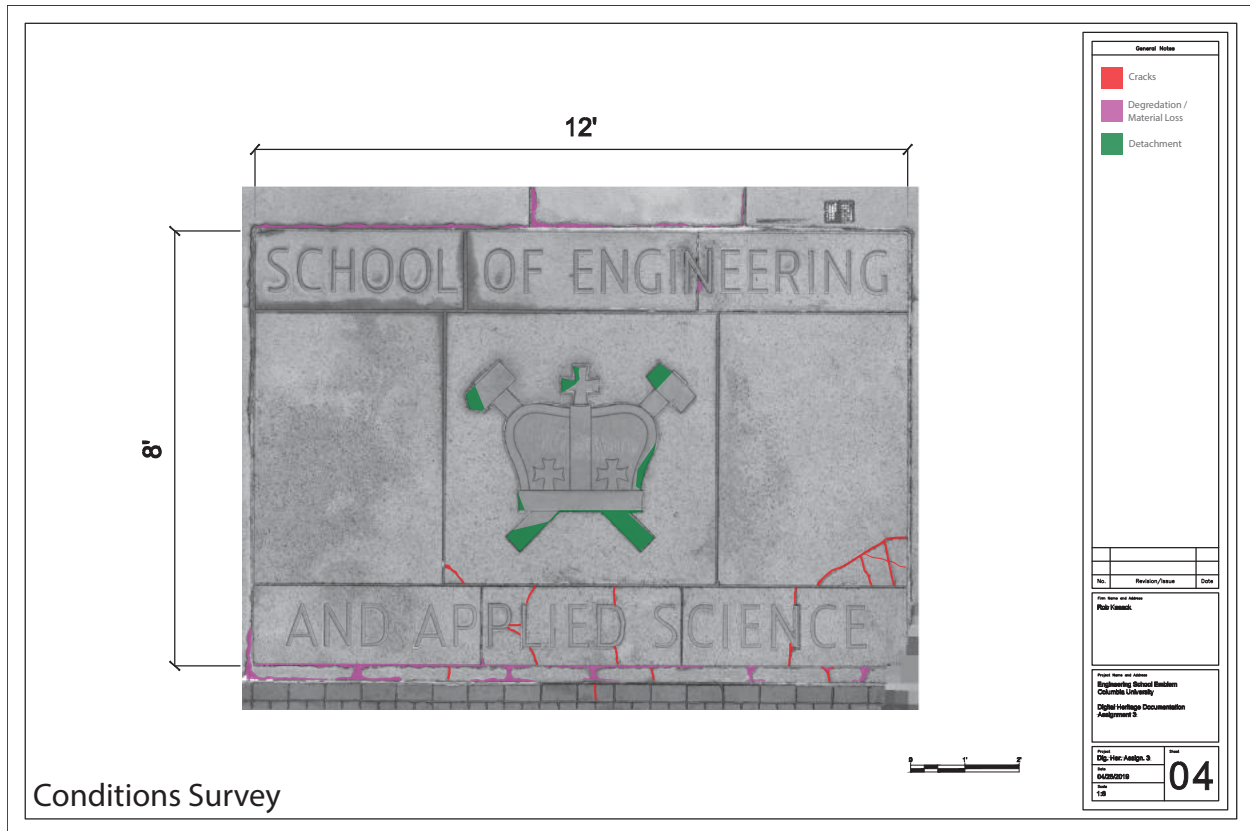


Figure 5-35. Orthographic image from 3D Model of School of Engineering emblem.

Above is an example of an efficient way to create a conditions survey without actually having to produce an architectural drawing

Summary of Experiment #2

This experiment proved effective for capturing a great amount of detail beyond that what is perhaps necessary for the production of line drawings and basic conditions documentation, much more interesting clear representation that some degree of limitation inherent to all photogrammetric programs. As seen in the photos on the following page, when comparing an original raw image file from the Nikon to a similar cropped area taken from the orthographic image rendered by RealityCapture, some information has been lost.

Specifically, look at a portion of the letter 'R', from the word Engineering, which, in reality, measures $2 \frac{3}{4}$ ". Here information degradation can be observed. The image on the top is the original raw photo taken with the Nikon D850. On the bottom is part of an orthographic image derived from the digital model of the emblem. These images are cropped at 600 percent, meaning what is seen here is 6 times greater than the physical image sizes. It can be noticed the image from the model, on the bottom, appears rather blurry and has lost a degree of detail. This is a result of the alignment process, where the software blends the multiple image set images into a composite. Some programs are better at this than others. Although this seems concerning, the orthographic image is very highly resolved and most likely retains enough data to serve many purposes in conservation-related documentation. An important consideration is this information isn't actually lost; the original data set is intact. The model can again be reprocessed, potentially resulting in a substantially better result that retains all of the detail as seen in the original photograph, by using another program or future upgrade.

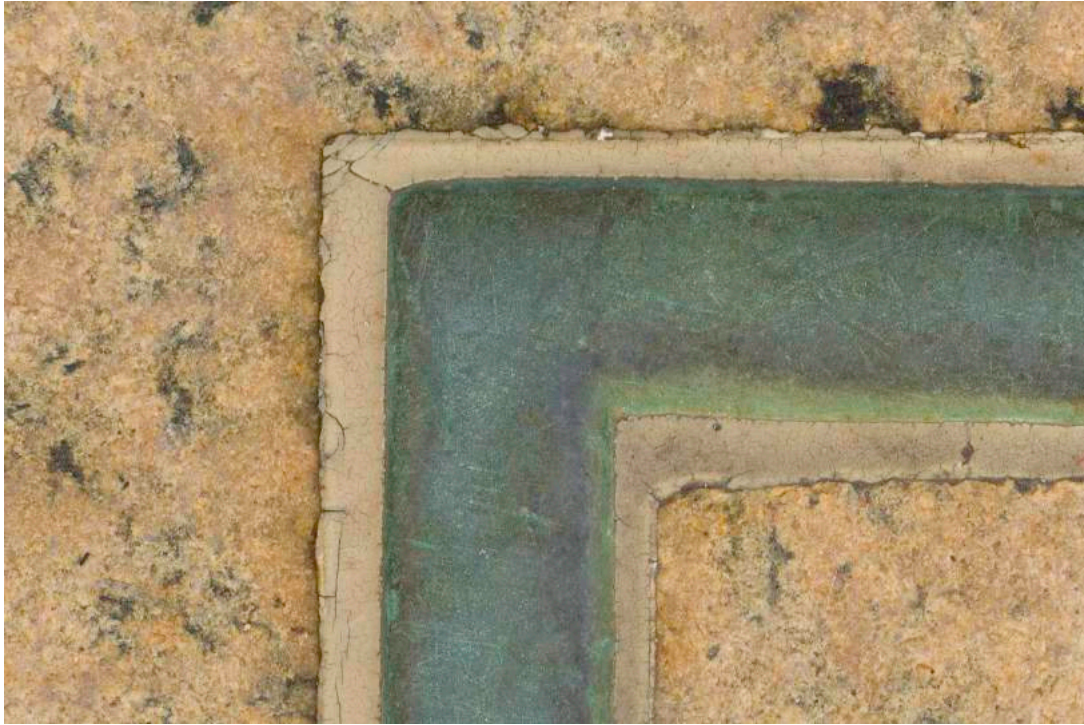


Figure 5-36. Original RAW photograph from Nikon D850.



Figure 5-37. Quality degradation due to the photogrammetric blending process.

Analysis of Software



Figure 5-38. Rendering of mesh from Metashape.



Figure 5-39. Rendering of mesh from RealityCapture.

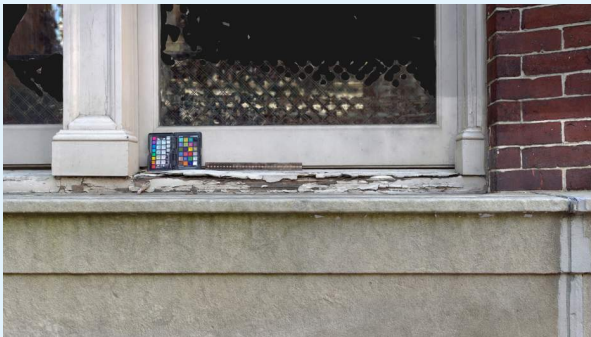


Figure 5-40 Rendering of mesh from ContextCapture.

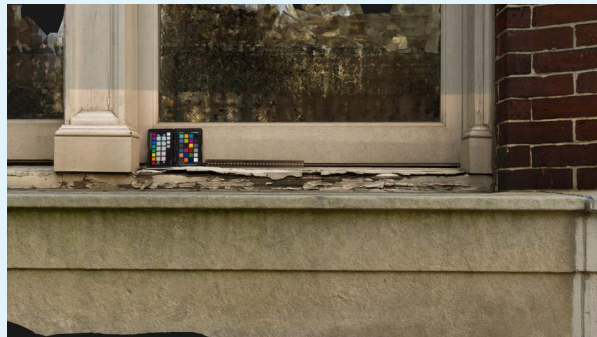


Figure 5-41. Rendering of mesh from Meshroom.

The above images are portions of the final reconstruction of the window sill at Avery Hall. The top left figure was produced in Metashape (Figure 5-38), the top right in RealityCapture (Figure 5-39), the bottom left in ContextCapture (Figure 5-40), and the bottom right in Meshroom (Figure 5-41). The models all were generated using the Nikon D850 data set. This level of control shows the positive and negative attributes of each program's processing ability. Of all the models, ContextCapture presented the best color rendition. The other three appear yellowed, having been somehow altered during the photogrammetric process. Somewhat surprisingly, RealityCapture took the longest to process the model at 11 hours and 36 minutes, Metashape followed at 8 hours and 5 minutes, then Meshroom, taking 4 hours and 51 minutes, with Context-Capture processing quickest, at 1 and 13 minutes.

Metashape Window Sill Model



Figure 5-42. Rendering of mesh from Metashape.

Aligned / Total Images	219/219
Time to Capture	6 minutes
GSD Ground Sampling Distance "Potential Resolution"	0.00003 cm/pixel
Reprojection Error (Root Mean Square Error)	0.994516 pixels
# of Points Generated	1,022,993
# of Triangles in Mesh	6,298,634
Total Processing Time	456 minutes
Unwanted Artifacts	holes, glass not reconstructed due to reflections, ghosting
Point Cloud File Size	11.5 megabytes (.XYZ)

RealityCapture Window Sill Model



Figure 5-43. Rendering of mesh from RealityCapture.

Aligned / Total Images	219/219
Time to Capture	6 minutes
GSD Ground Sampling Distance "Potential Resolution"	0.00003 cm/pixel
Reprojection Error (Root Mean Square Error)	0.366128 pixels
# of Points Generated	891,568
# of Triangles in Mesh	253,643,993
Total Processing Time	693 minutes
Unwanted Artifacts	glass not reconstructed due to reflections
Point Cloud File Size	28 megabytes (.XYZ)

ContextCapture Window Sill Model



Figure 5-44 Rendering of mesh from ContextCapture.

Aligned / Total Images	219/219
Time to Capture	6 minutes
GSD Ground Sampling Distance "Potential Resolution"	0.00003 cm/pixel
Reprojection Error (Root Mean Square Error)	0.6 pixels
# of Points Generated	1,693,616
# of Triangles in Mesh	3,381,108
Total Processing Time	73 minutes
Unwanted Artifacts	some artifacts with reflective glass, minor ghosting
Point Cloud File Size	N/A (too large to export)

Meshroom Window Sill Model

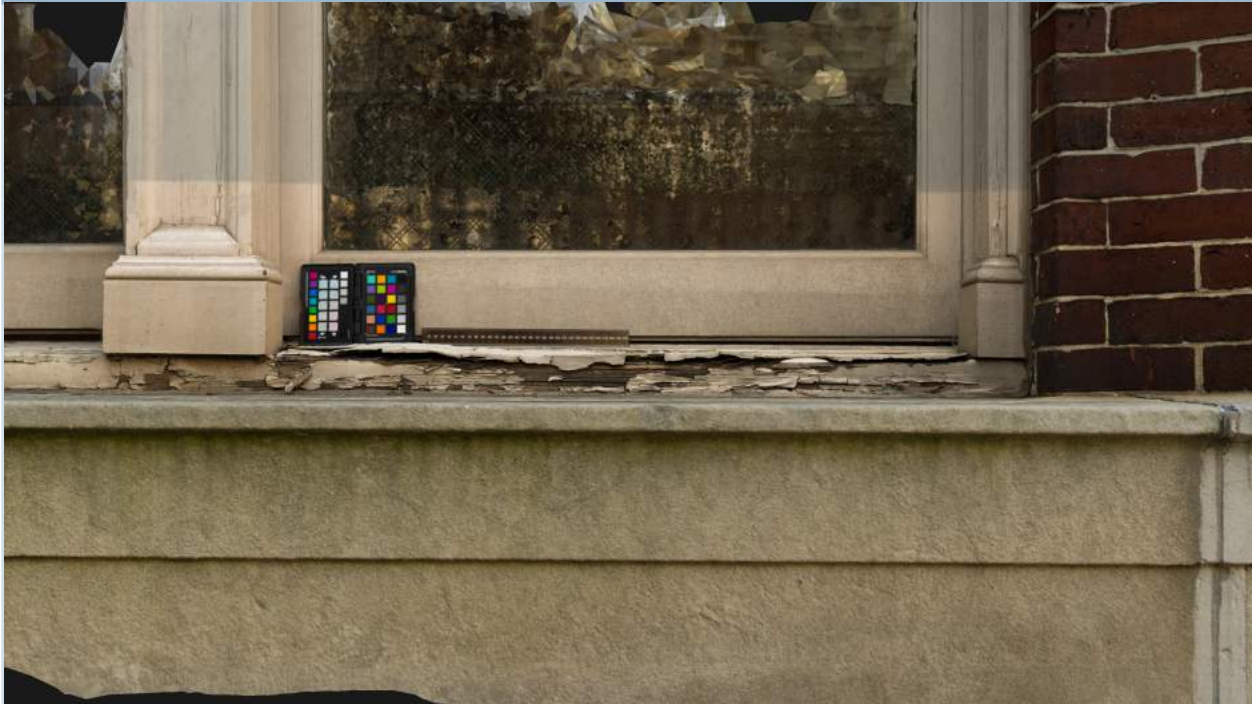


Figure 5-45. Rendering of mesh from Meshroom.

Aligned / Total Images	219/219
Time to Capture	6 minutes
GSD Ground Sampling Distance "Potential Resolution"	0.00003 cm/pixel
Reprojection Error (Root Mean Square Error)	0.975364 pixels
# of Points Generated	3,159,869
# of Triangles in Mesh	6,319,551
Total Processing Time	291 minutes
Unwanted Artifacts	minimal artifacts with reflective glass
Point Cloud File Size	20 megabytes (.PLY)

Summary of Experiment #3

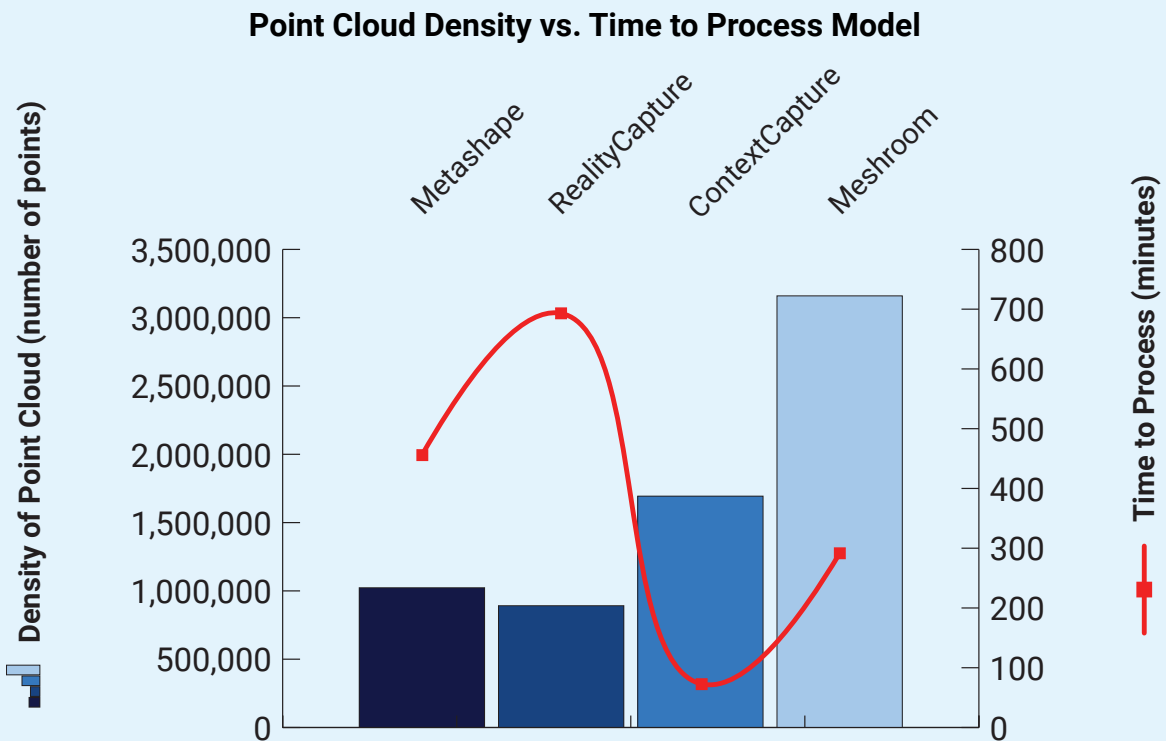


Figure 5-46. Graph comparing performance of photogrammetric software tested on window sill.

The graph above (Figure 5-46) illustrates two primary factors in the evaluation of the four photogrammetric programs used to generate the digital models of the window sill at Avery Hall. These two considerations are point cloud density and processing time. Notably, the two programs resulting in the least dense point cloud took the most prolonged period to process a complete model. Additionally, the open-source program, Meshroom, produced the densest, most information-rich digital model; it accomplished this in just under 5 hours, which translates to the approximate mean processing time for all four programs.

Dyckman Farmhouse Medium Format Capture Analysis



Figure 5-47. Raw Dyckman Farmhouse point cloud.



Figure 5-48. Filtered point cloud.

These are the results of the alignment of the digital model recorded by the Phase One and processed in Metashape. On the left (Figure 5-47) is what the raw point cloud looks like immediately after alignment. All of the busy and extraneous points visible are either peripheral, extraneous objects captured including trees, shrubbery, and other buildings), or they represent errors caused by reflection and other anomalies. Metashape gives the user the ability to manually clean and filter out these unwanted and erroneous points. Testing results indicate that with robust and critical filtering, Metashape can greatly reduce the error from the initial alignment. In doing this, the issue of the blurry orthographic photo of the Engineering School emblem possibly could have been mitigated. On the right, the ghostlike filtered image (Figure 5-48) shows the Dyckman Farmhouse before being processed. On the following page are some examples (Figures 5-49, 5-50, & 5-51) of quick orthographic visualizations that can be made using only the point cloud data.



Figure 5-49. Orthographic elevation from point cloud.



Figure 5-50. Plan from point cloud.

Figure 5-51. Side elevation.

Hardware Configuration for All Experiments



Figure 5-52. Workstation, front view. **Figure 5-53.** Workstation, internal view.

Below are the exact components of the computer workstation (Figure 5-48 & 5-49) used for this photogrammetric study, custom-built in December 2016:

CPU: Intel i7-6700K

GPU: Asus ROG Geforce GTX 1080 (8GB VRAM with 1835Mhz boost clock)

RAM: G.Skill Aegis 64GB (4 x 16GB) DDR4 PC4-19200 2400MHZ

Motherboard: ASRock z170 Extreme 4

Storage:

1. System drive (OS & Applications): Samsung SSD 960 Pro NVMe M.2 512GB
2. Active projects drive: Samsung 850 PRO 2.5" SATA III 512GB
3. Storage drives:
 - a. Western Digital Black 6TB 7200 RPM
 - b. Seagate Barracuda 2TB 7200 RPM

5.2 Thoughts on Photogrammetry

Digital photogrammetry has closed many of the gaps left open by its pre-digital ancestor. Greater access to higher resolution camera systems (at reasonable price levels), more robust software and exponentially more powerful computing platforms have made photogrammetry a viable and globally tenable technique for documenting heritage. Despite these great strides in accessibility, practicality, and usability, the field of heritage conservation still seems rooted in 2D methods as a means of communicating and interpreting conditions of historic structures.

The future of photogrammetry needs to continue to press to find ways in which this not-fully-realized technological tool can more fully be used to take advantage of its ability to visualize important information in three dimensions. Practitioners of different backgrounds should be able to communicate with standard applications and interfaces that exhibit their studies and surveys in a sculptural and interactive way. 2D output should no longer be the defacto standard of presenting data.

Currently, applications for digital photogrammetry within conservation primarily rely on 2D output. This method has been the way ever since its practicality for the field was realized. 3D outputs would undoubtedly represent a more natural way to portray built heritage, and could perhaps lessen or entirely remove the prerequisite for architectural training to understand some of the most essential building documentation.

This is not simply a call to blindly toss aside a proven and practiced method of the past. This push for a three-dimensional ontological, database-driven survey system is a necessity. Generating these types of visualizations in a 3D world can more closely resemble reality than anything produced on flat paper. Bridging the gap between practitioners of any background is possible by visualizing things in three dimensions. What is seen takes no special skill set to understand. Anyone working at any capacity with built heritage will be able to utilize this data. The possibilities for collaboration, with more transparent communication and expedited understanding, can ease some of the more

difficult hurdles in the most complicated of projects.

Until recently, this notion of working with photogrammetric and other digital data in such a practical and visual way was pure fantasy. Within the last few years, several teams have been at work trying to accomplish exactly this. Still, we are in the early stages of these efforts. They continue to be costly, rudimentary, proprietary, and largely impractical. More energy and research must be designated for understanding how experimental systems like these can be improved. How can these fragmented and exclusive systems be made more viable and accessible to all?

There are still specific technical skills and areas of knowledge required to understand photogrammetry for heritage preservation. Certainly, any person can purchase a decent camera and work with the software tested in this study. That fact does not, however, diminish the importance of critically understanding the principles of architecture as applied to preservation. Clicking a start button with a mouse does not make a person a practitioner or technician. There needs to be a far more in-depth look at how to educate and equip those “public curators” all around the world carrying their phones with them and documenting heritage sites everywhere.

Computer technology is continually evolving, yet the computer hardware we use seems unable to handle the high demands of the increasingly large image files produced by the newest digital cameras capable of much higher resolution. There is a challenge out there for software developers to make the elaborate and gigantic project files that practitioners often work with more practical. Still, too much time is spent waiting for digital models to be processed; and unfortunately, sometimes our systems crash during this process. There is some promise in cloud-based grid-computing. But even that seems to be reserved for the technical experts and those with very deep pockets. Advances in processing on a more feasible and local level are needed to make photogrammetry more approachable and useful for the smaller organizations without big budgets or staff.

Artificial Intelligence, at present, is a burgeoning industry. The quantum leaps

made in computational proficiency astound us with every passing year, at a rate seemingly beyond that exclaimed by Moore's Law. AI is being used widely in fields such as marketing, medicine, and robotics, yet has barely been spoken of with reference to heritage conservation. If machines and programs can generate original works of art, and robots can climb mountains and open doors, why then cannot the same technology make it possible to predict and monitor the most complex material conditions on a building? The technology is available, but more research and experimentation needs to be done.

Photogrammetry is our future, but it is very much with us today. It is used in a wide array of fields from robotics, cinema, and even fashion. 3D technology is becoming a part of our culture and photogrammetry is helping to create a new cultural identity for us all. Our lives have become increasingly digital, from connections with our friends to a more global heritage and a shared sense of history.

Digital photogrammetry has taken old technology to new levels of practicality. With some very inexpensive cameras or other common devices like cell phones and tablets, it is now possible to produce very competent architectural models in the field and for little expense. But quality is a relative thing.

The two images on the following page represent the relative difference in the physical size of an image as recorded by the iPad (Figure 5-54, on the left) and an image captured by the Phase One XF medium format camera (Figure 5-54, on the right). There can be no denying the sheer difference in scale of these two photographs. An image captured by a camera with a sensor as large as that in the Phase One is assuredly able to record a far greater level of information than any other camera with a sensor of lesser dimensions. This was verified in both the visual and quantitative analysis of the various digital models. Medium format images do very definitively result in greater quality output. A camera's sensor has a significant influence on the level of quality one can expect from their photogrammetric models.



Figure 5-54. Representation of actual file size of an iPad compared to a full-frame medium format camera.

Making the medium format approach even more enticing is the fact that camera rental houses now have global reach, thanks, in part, to the Internet. Because of this, some of the most expensive imaging equipment, such as the Phase One, can be rented for a fraction of the cost of outright purchase. This creates access to some of the best equipment when a job truly calls for the highest imaging standards.

As impressive as the Phase One was in these experiments, other smaller, more affordable options like the Nikon D850 (and even the ten-year-old Canon EOS 7D) produced exceptionally detailed results. These camera formats are far more practical than something the size of a medium format camera and are vastly superior to the results exhibited by the iPad. The iPad might be best reserved for those who may not already have a professional-grade camera, and instead want to use a device they already carry around daily.

As has been demonstrated, the recording device is an essential component in the photogrammetric tool kit, but it is not the only influential part of the pipeline. Software plays a large role in how an object is interpreted digitally and how it ultimately is dealt with

by those caring for historic buildings. It is not only important to have a speedy program that can produce results in minutes rather than days, but it is sometimes required to have a product that produces digital models and other output at consistently high levels of quality.

One of the best-performing programs in these tests was the completely free Meshroom by AliceVision. Meshroom seemed to keep up with the quality of the models generated by some of the more expensive offerings. In particular, it handles reflective surfaces, such as windows, the best of all. Open-source programs like Meshroom represents the next stage in photogrammetry for applications such as architectural conservation. In a competitive field, and one in which budgets are tight, this type of software product provides a certain degree of power and proficiency for the work of the modern cultural heritage practitioner.

References

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