SCANNING USING A SMART PHONE FOR HERITAGE CONSERVATION:

A Case Study Using the Reunion House

by

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Abstract

3D scanning, as a digital documentation and analytical tool, has been practiced for decades to support the decision-making process for heritage conservation. Site surveying, condition monitoring, documentation, educational presentation, and other traditional aspects of heritage conservation are supported using 3D scanning data today. Considerable previous literature has demonstrated many of its abilities to support conservation goals and its great potential for expanding capabilities. However, the high cost of current professional 3D scanning often becomes a deterring factor for less well-funded projects and projects with accessible related issues.

The development of smartphones and tablets equipped with built-in sensors, such as cameras and LiDAR systems, has opened up the possibility of using them as cost-effective tools for gathering geometric data for cultural heritage. This alternative approach could revolutionize the way heritage conservation professionals collect and visualize data. The enhanced accessibility of scanning with smartphones provides a chance for students, professionals, and the public to engage in the data collection process, thus fostering the sharing of knowledge all over the research value chain.

The ability of the proposed methodology with selected smartphone application and computer software to fulfill heritage conservation goals was tested in test scans and the case study. The case study is the master bedroom of Reunion House designed by Richard and Dion Neutra, which was built in 1951. Specifically, evaluation of iPhone 13 Pro built-in LiDAR system accuracy through iOS application SiteScape, and the digital products' availability and effectiveness from such device was conducted by comparing to the performance of a Leica RTC 360 professional scanner. Furthermore, smartphone competence in creating 360-degree photographic virtual tour was demonstrated with Matterport Capture application. Through an analysis of the acquisition process, registration, and point cloud quality, the strength and limitations of the smartphone scan method are discussed. The point cloud acquired with iPhone 13 Pro exhibited a 2% of

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error within the range of 17 feet compared to the point cloud captured by the professional scanner. The iPhone 13 Pro acquisitions were shown to be an accessible solution to quickly acquire spatial information with a lower level of detail with a low-cost.

Keywords

Smartphone, 3D scanning, Point clouds, Heritage conservation, LiDAR, Handheld mobile laser scanning

Hypothesis:

In the field of heritage conservation, adequate 3D spatial data for generating floor plans, building condition recording, and digital reproduction for educational purposes can be acquired by using the capabilities of a smartphone rather than using expensive professional 3D scanning equipment.

Objectives:

1) Identify the suitability of the new 3D smartphone-based scanning method for heritage conservation purposes.
2) Develop a digital documentation workflow for heritage conservation that involves low-cost scanning.
3) Test the suitability of several overlapping point clouds to create a more precise 3d model

Chapter 1 Introduction

"Historic preservation is an important way for us to transmit our understanding of the past to future generations" (National Park Service, 2021). Various previous practices, from archival research to site surveys, building maintenance to public education have been carried out to support the purpose of heritage conservation. The growth of technology in the last few decades has created many alternative methods for reaching a deeper understanding and recording of the existing built environment. 3D scanning instruments and techniques have become available to improve the quality of data collection for preservation-related works. However, not all cultural heritage projects can benefit from many of these advanced technologies. The issue of authorized heritage discourse (AHD) lies in both intellectual and physical accessible levels that constrains the debates about the meaning, nature, and value of heritage (Smith, 2006). From an operational perspective, the typically high expense of professional geometrical data capture and processing places obstacles for people of all levels to access and capture information. To overcome concerns about the affordability, accessibility, and usefulness of 3D scans of heritage sites, a method of using the built-in systems on a smartphone was tested at Richard and Dion Neutra's Reunion House. The methodology is expected to support local-level heritage conservation projects and heritages in endangered conditions and inaccessible locations with low-cost and easy operation on obtaining valuable data.

1.1 Heritage Conservation and Technology

Heritage conservation benefits from advances in technology in various aspects. Advanced tools support people in the field to protect endangered valuable cultural heritages with better performance. Conservation goals are achieved, and the results led to the next level with quickly updated technologies. At the same time, many participants in heritage conservation may not benefit from the technology because of limited funds. Cost-effective concerns constrain the scope and depth of heritage conservation projects. Alternative options are available to acquire useful data with an affordable device and accessible operation.

1.1.1 What is Heritage Conservation?

Heritage conservation (HC) is a discourse seeking to preserve, conserve and protect buildings, objects, landscapes, or other artifacts of meaning and identity-making, socially and culturally (Duluth Preservation Alliance, 2022). People look at history, ask questions, and learn new things about themselves through the lens of heritage conservation. It is important for people to transmit their understanding of the past to future generations.

The National Park Service has produced standards and guidelines that govern preservation efforts at the national, tribal, state, and local levels to ensure uniform procedures. The *Secretary of the Interior's Standards for the Treatment of Historic Properties* provides guidance for heritage conservation professionals to conduct their work (Norman et al., 2018b). The guidelines address four overarching treatments under preservation action: preservation, restoration, rehabilitation, and reconstruction with standards. Guidelines provide general design and technical recommendations to assist in applying the Standards to a specific property. Together, they provide a framework and guidance for decision-making about work or changes to a historic properties (National Park Service).

1.1.2 What do we conserve?

Works of art and other elements of human creativity are preserved and protected through the recognition of their cultural significance and the condition of their integrity. This recognition has shifted from individual structures to entire territories, with cultural content seen as essential to their preservation (Jokilehto, 2021). It is this recognition that has allowed for the preservation and protection of both tangible and intangible heritage. Tangible heritage that carry the intangible heir from past generations contribute to forming an identity within social and cultural life. UNESCO defines cultural heritage broadly as "the legacy of physical artifacts and intangible attributes of a group or society that are inherited from past generations, maintained in the present, and bestowed for the benefit of future generations" (UNESCO). The value of heritage sites, places, and objects are required to be understood with the context. Studying the physical heritage provides crucial evidence to reinforce the identity formed from it. The conservation of substantial property demonstrates a recognition of the necessity of the past and its value as societies of different times cherish values with various standards, the measure of heritage changes. The physical attributes of heritage may also be altered in the future; thus, recording current geometric conditions can be beneficial for future generation studies.

Heritage is not solely confined to material evidence, while the cultural significance being valued needs the vessel of substantiality. The information in the conservation process is framed by a conservator's ability, which will be limited to the cognitive framework in which conservators operate (Sully, 2008). Sully's statement does not only apply to the post-colonial content of conservation but also a universal account that value is subjective. What is valued in the current social context may change in the future; material evidence helps lock the information from the past from being ignored or miss interpreted. Both the materiality and cultural significance of heritages shall be conserved.

1.1.3 How do we conserve?

Preservation, restoration, rehabilitation, and reconstruction are four categories of treatments for Heritage Conservation actions as defined by *The Secretary of Interior Standards for the Treatment of Historic Properties*. The four treatments serve different goals, including maintaining and retaining existing historical materials, adaptive reuse, returning to a particular period of significance, and recreating the vanished property (National Park Service, 2022b).

Before any conservation work begins, a thorough investigation of the property is required. Archival research and site surveys are conducted to expand the knowledge about the area. The investigation reveals the cultural and historic background of the sites, as well as their current physical condition. Based on the weights assigned to cultural and historic value, a period of significance and character-defining features (CDF) are determined. To serve different goals of conserving a building, alteration, designation, maintenance, education and other actions can be taken corresponding to the client's request.

The National Park Service's *Preservation Brief 35 Understanding Old Buildings: The Process of Architectural Investigation* indicates that documentation of a building should be done before any other preservation process. (Travis, 1994). A documentation that combines both graphic and written description provides the opportunity of studying a structure without visiting it. The records can be used to find out about things from the past that might be too far away, too hard to get to, or have already been lost. Documentation is also a backup to present and to reconstruct for unforeseen damage to significant structures. The Historic American Building Survey (HABS) was established by the National Park Services, the Library of Congress, and the American Institute of Architects in 1933. HABS recognizes that words alone are not enough to record and explain buildings, the pictorial representation is indispensable in this process. As an archive program, HABS is required to ensure the clarity, reliability, durability, and standardization of documentation. Quickly developed digital technologies change at a rapid pace, often before data can be migrated or stored. Thus, digital technology is considered only suitable as a tool to produce documentation, but not as a final product.

Documenting a property is one of the most intriguing aspects of preservation, and the study may be compared to solving a riddle. The potential significance of a structure is estimated referencing the four criteria listed in "National Register Criteria for Evaluation": association with events, significant person, distinctive architectural style, and history or prehistory (Norman et al., 2018a). Integrity is one of the qualities used to identify a property's historic importance. The National Register program developed Location, Design, Setting, Materials, Workmanship, Feeling, and Association as seven aspects to be evaluated in determining a structure's integrity (Norman et al., 2018a). Thematic and historic context is another important element in accessing historic significance, referring to the cultural setting in which the property was formed, as well as its subsequent history. The thematic framework, which includes eight categories that are built on people, time, and place, is encouraged by the National Park Services in the evaluation process (Norman et al., 2018a). This information can be found through deep research from photographs, old newspapers, legal documents from city maps and lithographs, Sanborn fire insurance maps, oral traditions, and observing the building itself.

An historic context statement is the document that provides an overview of the influence of construction traditions, development eras, and shareable character of places based on research and evaluation standards. It is a required document for many nominations and designations at various levels (Norman et al., 2018a). A nomination for the National Register of Historic Places will go through a review process from the states historic preservation office (SHPO) and the Secretary of the Interior in Washington, D.C.. Once approved, the property will be listed in the National Register and published in the Federal Register (Norman et al., 2018a). The National Register of Historic Places represents national recognition of a historic property, but it does not protect the structure from alterations or demolition (Norman et al., 2018a). Properties with exceptional value for the United States can be designated as National Historic Landmarks with additional evaluation and documentation. Both nomination and designation of the National Register and National Historic Landmarks require intensive investigation, documentation, and description to the property (Norman et al., 2018a).

Before any conservation treatment is undertaken, a Historic Structure Report (HSR) should be created to serve as a planning document. An HSR is a thorough record of existing historical research and resources as well as existing conditions (Slaton, 2005). It provides a forum to identify historic fabric and the means to minimize its loss, damage, or any adverse effects upon it (Norman et al., 2018a). From an understanding of the historic fabric, long-term alternative actions and their impact on the site as a whole can be explored in the planning phase (Burns, 2003). Its overall substance is a two-part narrative of the structure's developing history and recommendations for its treatment and application, as well as references to previous work. The essential is laying the groundwork for future practice to be done with precision, integrity, and sensitivity to the structure's historic and cultural value (Norman et al., 2018a). An HSR includes historic, architectural, engineering, analysis, landscape, archaeology and furnishing sections. The current condition of a structure is the main concern for the architectural data section (Burns, 2003). Buildings deteriorate overtime, and accurate measured drawing should reflect those changes. Recommended methods of recording a building's current condition including measured drawing, large-format photography, computer aided drawings, and videography (Arbogast, 2010).

All the efforts mentioned above dedicated to the conservation of Heritage resources contribute to the eventual purpose of benefiting future generations (UNESCO). We acknowledge the value of both cultural and historic significance together with the physical condition of heritage. The investigation and recording of tangible material evidence serve the disclosing of information. Constant maintenance ensures this material evidence deteriorates at a slower rate and education exposes such knowledge to a wider audience.

1.1.4 Heritage Conservation and technology – technology for Heritage Conservation

When the Mount Vernon Ladies Association saved George Washington's house in 1858, heritage conservation deployed a very different workflow compared to today's preservation (Mount Vernon Ladies' Association, 2022). Not only is the workflow growing more and more comprehensive, the innovation of technology also drastically changes the way people learn about the built environment. From measured drawing and photography to computer aided design (CAD) and 3D scanning, the advancement in technology assists heritage conservation professionals to achieve accurate and effective results.

1.2 Digital documentation

From measured drawings and printed photographs to computational drafting and 3D scanning, digital technologies are gradually becoming the dominant tools of documentation. Under the assistance of traditional methods, digital technologies can record capture detailed information of historic buildings, sites, and objects. The quick and accurate capture of exact measurements of a structure's dimensions, physical characteristics, and details of its construction provide a platform for heritage conservation professionals to create detailed preservation plans (Gray, 2022).

1.2.1 2D documentation

Measured drawing and photography are the two most commonly used documentation methods. Paper based drawing and large-format black and white photographs are especially praised for the permanence and accessibility for long term archival storage (Library of Congress, 2011) (Figure 1-1). They are also the preferred file format for HABS. Original drawings and negatives were scanned and digitized to Library of Congress Digital Collections.

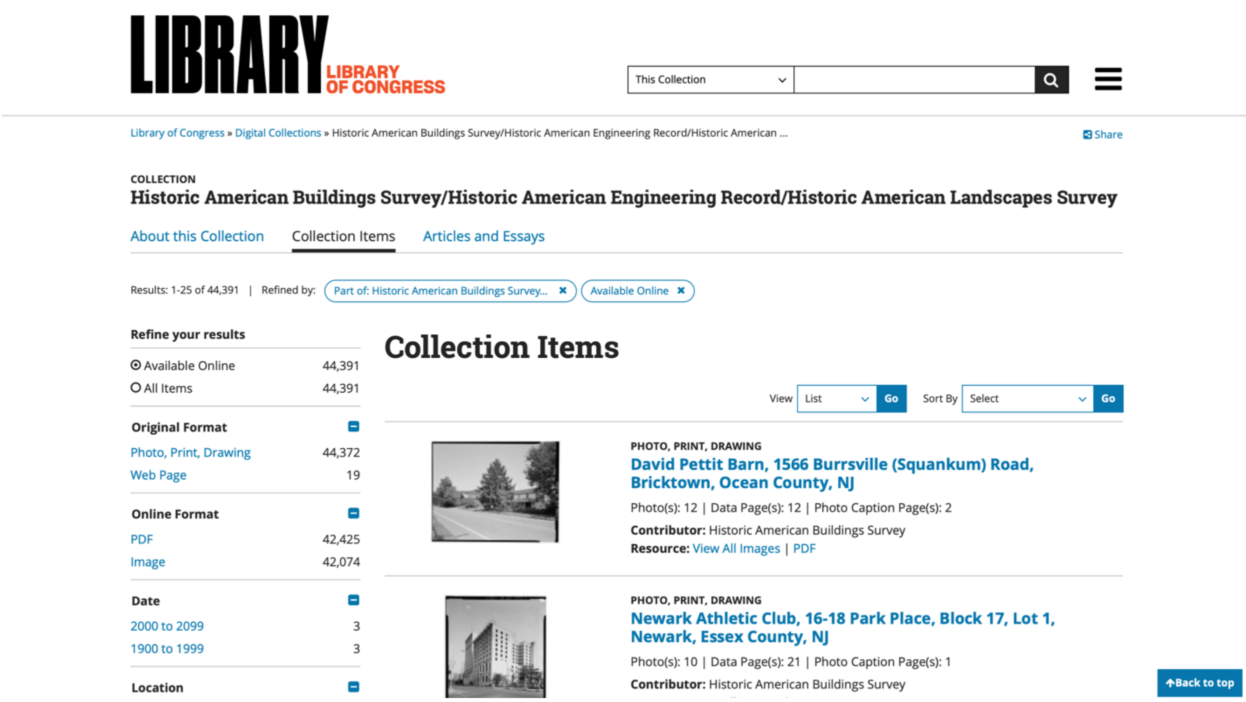


Figure 1-1 Library of Congress HABS Online Database Digital Collection (Library of Congress HABS Online Database Digital Collection, 2022)

Measured drawings

Measured drawings are a detailed form of architectural and engineering documentation that accurately portrays a three-dimensional structure or site in two dimensions (Fig. 1-2). This process involves translating the cultural values of a three-dimensional object into two-dimensional illustrations and serves many purposes, such as planning restoration or rehabilitation work, recording a structure facing imminent demolition, aiding in the normal maintenance of a structure, protecting against catastrophic loss, or as part of a scholarly study (Akboy-İlk, 2017). These drawings can be utilized for a variety of purposes, such as planning for restoration or rehabilitation of a structure, recording a structure facing imminent demolition, aiding in normal maintenance, or as part of a scholarly study (Norman et al., 2018a).

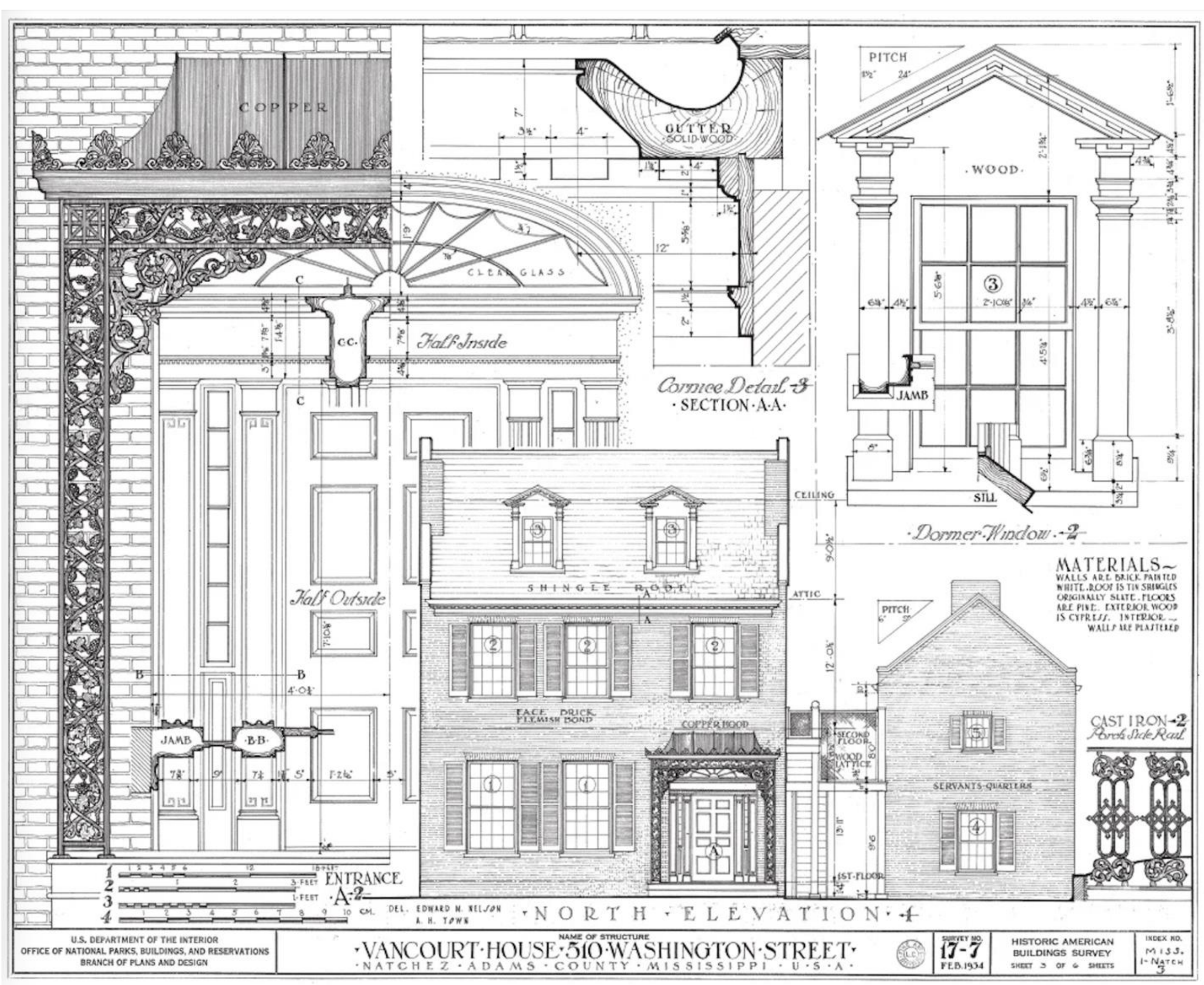


Figure 1-2: Measured drawing example

The production of a measured drawing involves making decisions about the significance of the structure and the scale, features, and level of accuracy to be included. Documents, hand measurements, and photographs are the main sources of information used to capture dimensions (Burns, 2003). Dimensions recorded on field notes are the primary source, and they often contain more dimensions than are included in the final drawing. This method helps architects and conservators become familiar with an object and discover subtle aspects (Eppich & Chabbi, 2007). The smallest unit of measurement in a drawing is determined by the scale. For example, the most common architectural scale is 1/4" = 1'-0" with a smallest unit of 1", while hardware, tools, and moldings can be measured down to 3/32" in a 3"=1'-0" scale (Burns, 2003).

Measured drawings produced by hand are one of the costliest types of architectural and engineering documentation due to their prolonged production time. When budget or time is limited, sketch plans can be used in place of measured drawings. Although they may not be accurate in scale, sketch plans should show elements in their correct proportions relative to one another (Burns, 2003; Norman et al., 2018a).

Film

Photography is the most often used means of documention. Photographs are simple to understand and can convey information that other types of documentation cannot. It is capable of conveying three-dimensional features, spatial linkages, present situations, texture, and context, which are difficult to express in writing or painting (Burns, 2003). Careful photography can be both aesthetically pleasing and informative (Burns, 2003). While it may not be a replacement for drawings, histories, or even viewing a structure or site in person, it offers a unique perspective and a way to keep structures alive in the future.

Other than drawings and written descriptions, large-format photography is the official format for HABS documentation of structures and buildings. HABS encourages large-format photograph not only because it capture more information, but also because of the stability of black and white negatives. With archival longevity as the goal, original large-format negatives will survive more than 100 years with careful handling and storage, then produce prints with no degradation of the image (Burns, 2003). The National Park Service also published *Heritage Documentation Programs HABS/HAER/HALS Photography Guidelines* in 2015 to instruct conservators taking photography for documentation purposes, including equipment, view, format, etc., regarding various types of built environments (Burns, 2003). Architectural photography should follow the same shared principles. An understanding of the subject, proper lighting, scaling tools, and aesthetics are common standards for photography taken by either in large-format, 35mm, or digital cameras.

The use of digital photography has become the accepted method for recording the current state of historic sites. It can be used to supplement or replace hand-drawn sketches by being incorporated into computer drawings. Another method of photography is rectified photography; as Getty's *RECORDIM: Guiding Principles & Illustrated Examples* defined "[it] is the process of photographing a facade by aligning the images to be as parallel as possible to the section of facade to be recorded (Eppich & Chabbi, 2007). Using this method, it is possible to obtain the dimensions of a building from a photograph rather than having to take time consuming measurements on the site. X-ray photography and radar on building structure can identify materials and structures behind the surface (Norman et al., 2018b).

Two-dimensional photography is the dominant method of digital documentation for its easy process to capture, editing, share, and view. In building survey phone apps such as Fulcrum, a photograph of the property is required at the end of each description. However, a photograph can only capture information from one point of view. More details of the building need to be pieced together with photographs from various perspectives and distances. Even with such detailed documented photographs, one still needs to transform the two-dimensional visual information, through their mind, into three dimensional objects.

Therefore, directly documenting properties with three-dimensional spatial data reduces the deviation created by differences in human perception, which optimizes the understanding of architectural features and their significance.

Figure 1-3: Film photography of Reunion House living room (USC Library, 1951)

1.2.2 360-degree photographs

360-degree photograph is a controllable panoramic photo taken on the original point from which the shot was taken (Panoraven, 2021; TechTarget Contributor, 2016). Shooting photographs at one location of many angles, a full spherical view was then created in a raw 360-degree photograph (Fig. 1-4) (Burns, 2003; Panoraven, 2021). With software or application, the 360-degree photograph can be navigated in different directions, as one standing and looking into different directions (TechTarget Contributor, 2016). 360-degree photographs are different from 3D stereo photographs (Fig. 1-5), which adds a third dimension to photographs. To view the depth inside a 3D photograph, special 3D glasses are used.

Figure 1-4: Raw 360-degree photograph (Panoraven, 2021)

Figure 1-5: 3D photograph (Bak, 2017)

360-degree photographs can be taken by a smartphone with a certain application, a 360 camera, or a Digital Single Lens Reflex camera (DSLR) (Panoraven, 2021). 360 cameras came from different companies and make, for example, Insta 360, Ricoh, and Matterport. Smartphone applications that capture and generate 360-degree cameras including 360 Pro, Panorama 360, Matterport Capture.

360-degree photographs are common in the survey and real estate industry. The most well-known examples are Google street view and real estate virtual tours (Fig. 1-6). Even though 360-degree photographs provide more spatial experience, it does not obtain any depth data.

Figure 1-6: Google street view of Forbidden City

Matterport 360-degree photographs are also commonly used in generating virtual tours. As shown in Fig 1-7, through a browser, one is able to move between different camera capture location and visit 360-

degree view of the place described. Assisted with Virtual Reality equipment, 360-degree photographs can be experienced in virtual environment.

Figure 1-7: Michael White Adobe virtual tour (AQYER, 2022)

1.2.2 3D documentation using scanners

The use of 3D scanning is becoming increasingly popular in heritage conservation as it improves efficiency and accuracy in acquiring, analyzing, and presenting information. 3D scanners nowadays can be equipped with a mobile device or a drone to complete tasks within several hours that used to take weeks by labor-intensive measurements. Through algorithms and mechanisms, precise data with high accuracy and resolution is captured and presented. However, the high expense of scanning and experts operating that data place barriers for projects with fundraising issues.

The two barriers are clear: the high expense of renting or owning high-end scanning equipment and the sophisticated operation and registration process of visualizing point clouds data. The two challenges are so interrelated that they usually come simultaneously. The issues are expected to be mitigated with a smartphone equipped with a relatively high-resolution camera, embedded LiDAR system, and installed data processing applications. LiDAR began to be installed in smartphones in 2020 with Apple company releasing its new model of iPhone 12 Pro (Luetzenburg et al., 2021). Appropriate use of a smartphone can assist property owners, cultural resource managers, and other stakeholders with the initial survey, documentation, maintenance, and education to evaluate the necessity of hiring experts on any of these areas with the higher expense and explore the possibility of achieving these tasks with an acceptable amount of detail in an affordable and accessible method.

Another scenario that can benefit from the methodology is for heritage sites endangered or located at an inaccessible place. Heritage in a war environment or with difficulty in transportation is greatly endangered. These resources beg for more attention, but due to their inaccessibility, it is hard for heritage conservation professionals to protect the site and pass the heritage onto future generations. Smartphone scans allow non-technicians to acquire geometrical data of such heritage property and share point clouds with specialists remotely.

Acquiring three-dimensional spatial data from architectural features can be achieved through 3D scanning techniques. While with the development of science and its application, there are dozens of 3D scanning equipment and techniques available for different purposes. There are a number of 3D scanning methods based on different working principles, in various working environments, and multiple levels of precision and accuracy. The most well-developed and extensively deployed are 3D scanners working in triangulation, structured from light, photogrammetry, pulse, Phase-Comparison, and 3D photography equipment such as Matterport and 360 cameras. For 3D documentation methods, point clouds are a universal file format that further data processing can be based (El-Ashmawy & Shaker, 2014).

Point clouds as its name indicated, are clusters of data points. This group of points with each point defined in Cartesian coordinates (X, Y, Z) describes a three-dimensional shape. Point clouds are different from a surfaced 3D model of Building Information Modeling (BIM) because it does not have a surface and does not include information beyond spatial data (Park & Lee, 2019). With software such as Recap Pro, a point cloud can be used to generate a surfaced mesh model. The measurements using mesh models are believed about 2%–3% smaller than those using direct point clouds (Fig. 1-8) (Park & Lee, 2019). The triangular mesh quality can vary significantly in terms of the point density, the algorithm, or the complexity and shape of the object surface (Park & Lee, 2019).

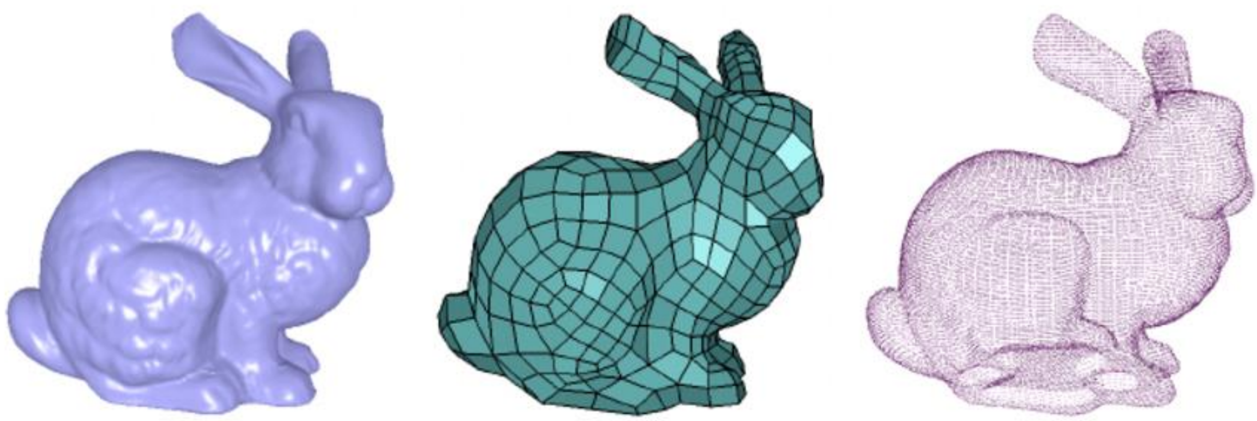


Figure 1-8: Point Clouds, Control Mesh, Result visualization of a rabbit (Yoon, 2006)

A point cloud is a series of 3D points. However, most 3D modeling software programs are designed to handle meshes, and while going from a point cloud to a mesh is easy for a simple object, it is extremely difficult separating it into multiple objects (Fig. 1-9.) Point clouds can also be associated with textures (Fig. 1-10)

Figure 1-9: Conegliano Italian Synagogue - Point Cloud (Caine, 2019)

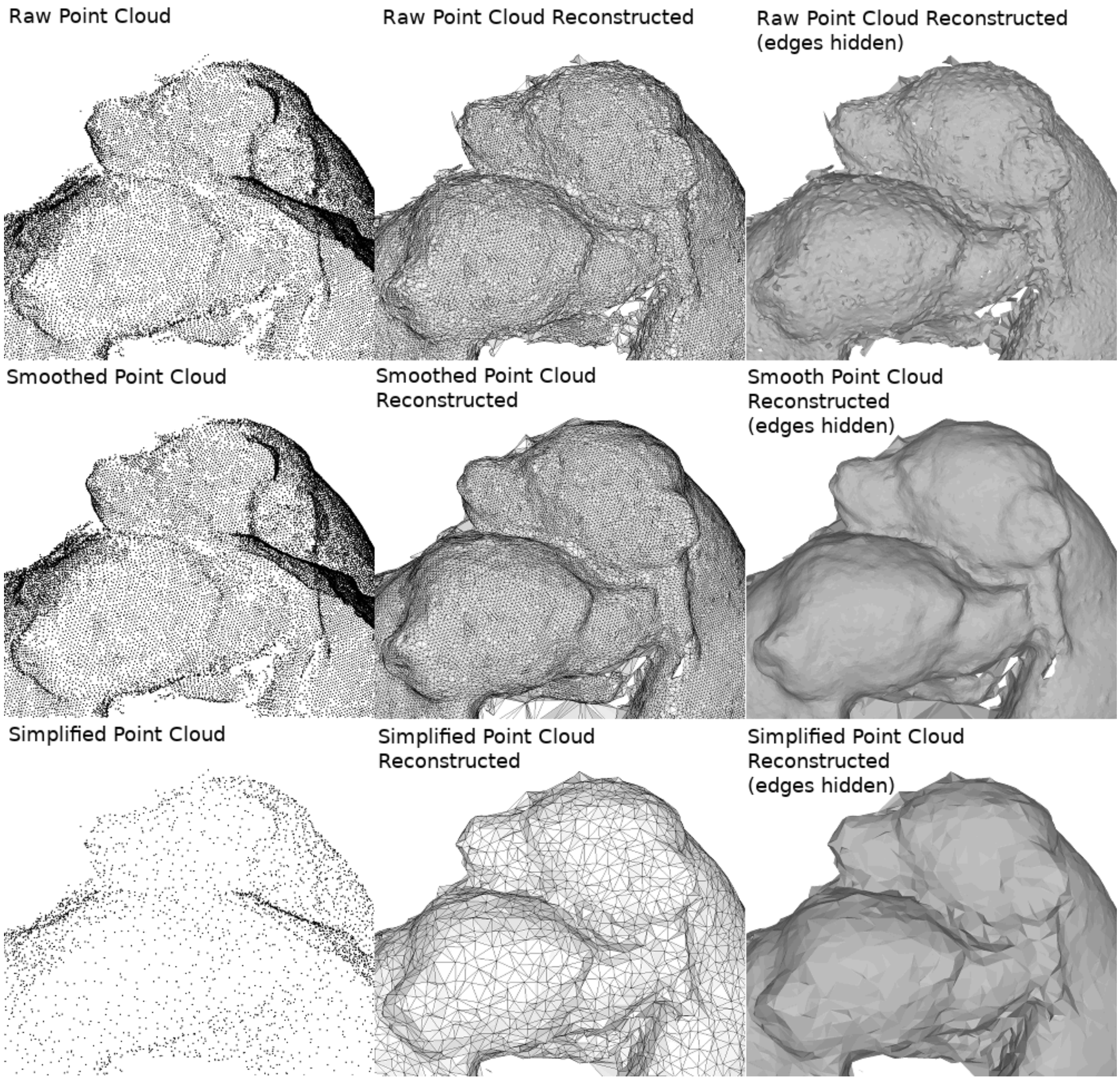


Figure 1-10: Same point cloud data with different processing in reconstructing surface (Giraudot, 2022)

Triangulation Scanner

The triangulation scanner is named because of its working principle that the emitted laser and the reflected laser light form a triangle (Acuity Laser, 2022). Through calculating the triangulation of the position of a spot or stripe of laser light, the scanned object can be calculated to shape. More accurately speaking, the light of a laser through a rotating mirror shoots onto the subject. The mirror turns to deflect the light to thoroughly scan around the subject. In this process, each reflected beam of laser is focused onto the sensor or camera by another lens (Fig. 1-11). The location of the point on the sensor, the known separation (D) between the lens and the mirror, and the recorded angle of the mirror combined provide a 3D coordinate based on basic trigonometry (Boardman & Bryan, 2018).

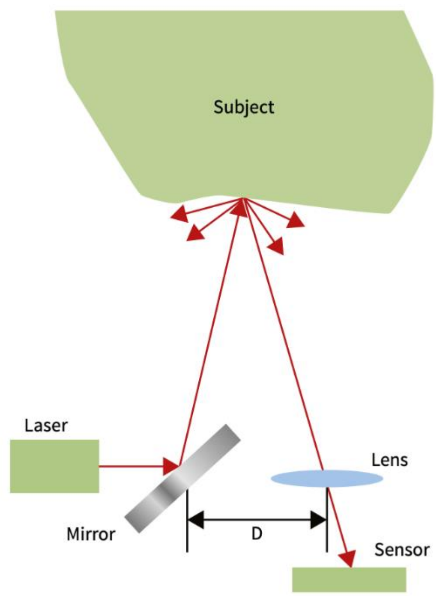


Figure 1-11: Working principle of triangulation scanners (Historic England, 2018)

Structured Light scanner

Structured light scanners, illustrated scanners, and some handheld scanners all share similar working principles as the triangulation scanners with some variations. The difference between structured light scanners with triangulation scanners is the amount of light or laser shot onto the subject. A structured light scanner emits a "sequence of organized patterns of light," projecting on the object's surface (Fig. 1-12) (Wachowiak & Karas, 2009). The distortion of the light pattern is analyzed and the distance of every point is calculated using the surface topography (Raychev et al., 2017)

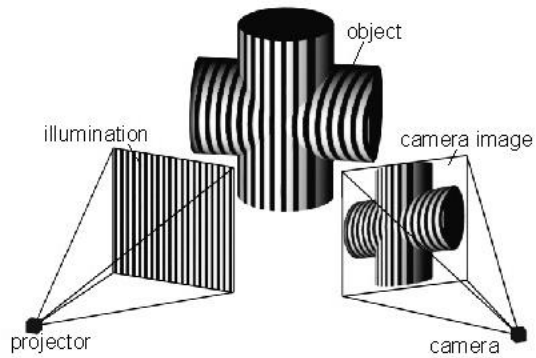


Figure 1-12: Working principle of Structured Light scanners (Bitfab, 2022)

Structured Light scanners are most often used in common range heritage documentation and both types of scanners capture excellent surface and color data (Boardman & Bryan, 2018; Wachowiak & Karas, 2009). Its relatively low cost compared to other professional scanners ($100,000–$200,000), portable system, together with the accurate spatial registration make these types of scanners highly desirable for heritage documentation work (Wachowiak & Karas, 2009).

While its scan quality is largely determined by the control of environmental light, which adds difficulty to operation (Boardman & Bryan, 2018). It exhibits the best capability in darkened situations where the emitted and any ambient light are especially evident. The limitation of these scanners shows up when lighting conditions are not preferred. These conditions include an unclear view from both lenses to objects, deep undercuts on the object surface (where light cannot reach), highly reflective surface, reflectance, and transparency surfaces property, and ambient illumination (Agnello et al., 2005; Boardman & Bryan, 2018; Wachowiak & Karas, 2009). In addition, the triangulation and structured from light scanner work with a small to medium range (<10m), and are not suitable for large-scale architectural structures and topographical surveys (Wachowiak & Karas, 2009).

Photogrammetry

Digital photogrammetry was first proposed by Ian Dowman in 1984 to map the topography of terrain using satellite imagery. Three-dimensional information is calculated and measured from two-dimensional photographs. Calculation of triangulation is the working principle of digital photogrammetry. Photographs taken from different locations have different “lines of sight” between each camera site to the object (Douglass et al., 2015). Through a mathematical process of the angle, location, length, and distance information of the line of sight, three-dimensional data can be produced. The quality of photogrammetry largely depends on the photographs used for calculation, including the photographs’ resolution and the area of overlapping on each abutting photograph (Fig. 1-13). Photogrammetry software for smartphones was also developed in the past decade. People are able to capture 3D data from a portable and affordable device.

Figure 1-13: Working principle of photogrammetry (Shet, 2022)

Pulse (TOF)

According to Historic England’s *3D Laser Scanning for Heritage Advice and Guidance on the Use of Laser Scanning in Archaeology and Architecture* “Pulse scanners use what can be considered to be the most straightforward technology: a pulse of laser light is emitted and the time it takes for the return flight is measured” (Boardman & Bryan, 2018). Light detection and ranging (LiDAR) is considered a typical pulse scanning method.

This functionality is achieved through a sophisticated mechanism timing the receiving of the laser light and a precise mirror on a rotation system. The system can be rotated 360° around a vertical axis and between 270° and 300° around a horizontal axis (Boardman & Bryan, 2018). Forming almost a complete sphere of view, the rotation system provides a great advantage to pulse and Phase-Comparison laser scanners compared to triangulation and structured light scanners (Boardman & Bryan, 2018) (Fig. 1-14)

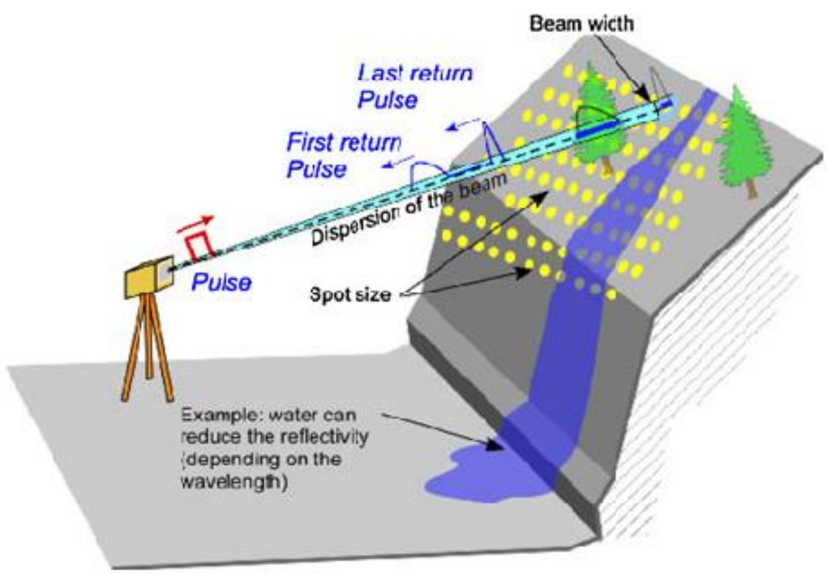


Figure 1-14: Principles of laser scanner data acquisition, showing the example of TLS (Jaboyedoff et al., 2012)

Similar to triangulation and structured light scanners, scanners with a pulse working principle can neither work on translucent nor reflective surfaces. The process of receiving signals back from such a surface may produce degradation of the quality of the range data, thus generating two critical issues for the geometry evaluation: a bias in the distance measurement, as well as an increase of the noise level (Agnello et al., 2005; Andrews et al., 2003; Haddad, 2011).

In the past, pulse scanners were criticized for their slow scanning process, and the last pulse of the laser cannot be emitted until the earlier one has been received. In 2015, Leica company released ultra-high-speed scanners with rates of 1MHz (1 million points per second) (Leica Geosystems AG, 2022c); later the same year, RIEGL released their VZ-400i Terrestrial Laser Scanner, achieving 1.2MHz pulse repetition rate (RIEGL, 2022), mainly shortening the time per scan.

A LiDAR scanner is commonly equipped with a tripod, mobile device, or a drone because the energy emitted in a single pulse of laser light is strong enough to support the system scanning from a great distance, typically up to 1km but in some cases up to 6km (Riegl VZ-6000). The vital energy in one laser pulse enables it to pass through a tree canopy and reach the terrain in airborne scanning. This characteristic also gives it an advantage over Phase-Comparison scanners in bright daylight (Boardman & Bryan, 2018).

Starting in 2020 when Apple company released their iPhone 12 Pro that is embedded with a LiDAR system, a growing number of iOS applications such as SiteScape enable geometrical data to acquire functions. Users can obtain 3D data and upload point clouds to a cloud based platform for further editing. SiteScape app allows either free or paid user licenses, which leads to different levels of services. With a free user account, one can scan with controllable parameters, and upload one data set at a time to the Cloud (Putch, 2022). While for a paid version, users can easily merge several scans together to generate a larger area of space, as well as multiple data being uploaded to the Cloud.

Phase-Comparison

Phase-Comparison scanners are similar to pulse scanners in that they are based on the round trip of the laser pulse. The difference is that instead of timing the roundtrip of a single pulse of laser light, Phase-Comparison scanners measure the wavelength difference between the laser emitted and the laser reflected (Daneshmand et al., 2018). Instead of a single laser pulse, Phase scanners emit a constant laser beam to the scanned surface. As the laser light shoots on the surface, some portion gets absorbed while others reflect to the scanner with a changed wavelength and frequency. The shape was therefore calculated through the difference in frequency (Suchocki et al., 2021). In HC projects, Phase-Comparison scanners performed well in capturing damage under surfaces. It can collect data much faster than structured from light and pulse scanners, but because the energy is lower and frequency can be disturbed, their effective distance is shorter. Due to the working principle of measuring frequency difference, phase-based scanners can be affected and create more "noise" and inaccurate data (Existing Condition, 2022)

1.3 Accuracy versus precision

Scanned data is commonly evaluated based on their ability to achieve certain goals. To better understand, the scanned data's quality, the metrics such as accuracy and precision are proposed.

Even though commonly obfuscated, accuracy and precision describe different aspects of data. Accuracy describes how close a measurement is to the true or accepted value. Precision is about how close measurements of the same item are to each other (Fig. 1-15) (Exploring Our Fluid Earth, 2022). In the case of scanning, accuracy can be determined as metric varied between scanners. On a product page, companies would exhibit system accuracy. Taking Leica P30/40 as an example, the company stated the scanner can capture points at a 3mm (0.12 inch) accuracy in a 50-meter (164 foot) distance (Leica Geosystems AG, 2022b). While even conducting the same scan twice without changing the scan location, the points obtained through scanners can be different. Points may not stand on the exact same spot as the previous scan. However, the repeatability of points is not heavily weighted in achieving HC tasks. In monitoring a structure or detecting cracks, the surface or line generated from the cluster of points is the evaluation standard for precision. Even if points are not standing at the exact same location, the surface or trend they generated is repeatable through various scans. Then it is said to be precise.

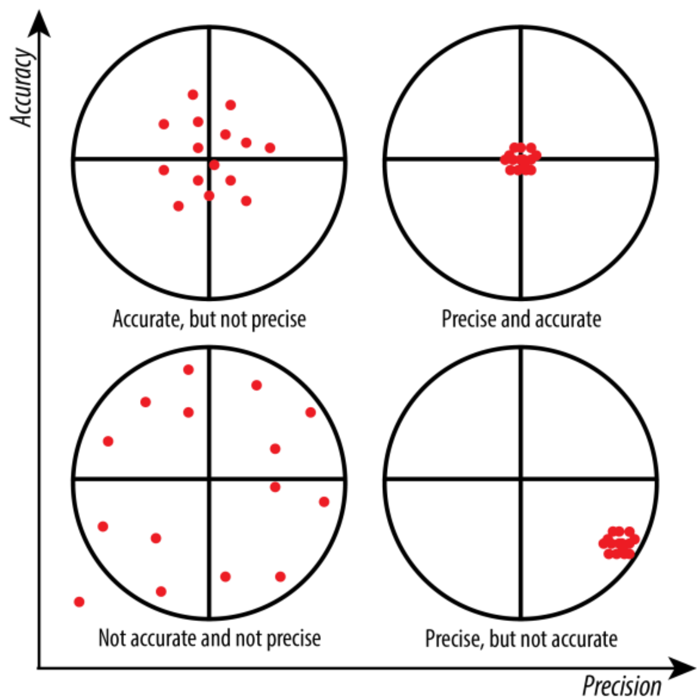


Figure 1-15: Precision VS Accuracy (St. Olaf College, 2022)

1.3.2 Accuracy of scanners

Scanners from different companies adopt different accuracy parameters. Scanners researched deploy an accuracy range from 3mm to 15 mm. The accuracy of scanners is determined by working principle, scanning range, and purpose. Accuracy data can be found in product page from company's webpage (Chart 1-1). A 3D accuracy chart extracted from product pages of 3D scanners. There is no clear requirement on the accuracy for achieving specific conservation goals (Gray, 2022). However, if the scanned data falls in low accuracy, it may not be able to review the movement of structure over time, or to detect and exhibit cracks.

Table 1-1: 3D accuracy of 3D scanners

	3D accuracy
ScanStation P50	4.4mm@50m 6.8mm@100m
ScanStation P40	3.2 mm @50 5.9mm @100m
ScanStation P30	3.2 mm @50 5.9mm @100m
RTC360	6.4mm @50m 12.5mm @ 100m
RTC360 LT	6.4mm @50m 12.5mm @ 100m
BLK360	6 mm@ 10m 8mm@20m
Focus Laser Scanner 350 Plus	2 @10m 3.5 @25m
Focus Laser Scanner 150 Plus	2 @10m 3.5 @25m
Focus Laser Scanner 350	2 @10m 3.5 @25m
Focus Laser Scanner 150	2 @10m 3.5 @25m
Focus Laser Scanner S70	2 @10m 3.5 @25m
FARO Freestyle 2	≤0.5 mm 0.5 mm at 1 m distance 5 mm at 5 m distance 15 mm at 10 m distance
Riegl VZ 400i	3mm@50m, 5mm@100m
Riegl VZ 600i	3mm@50m, 5mm@100m
Riegl VZ 2000i	3mm@50m, 5mm@100m
Riegl VZ 4000i	15mm
Riegl VZ 6000i	15mm

1.3.3 Point Cloud data processing software

Point cloud data cannot be visualized, processed or edited without software. There are a number of software programs that are designed to work with point cloud files. Some were written by scanner companies, while others were developed by technicians. Among these software programs, most requires paid user licenses, CloudCompare and Meshlab are two that offer free download and functions. Meshlab emphasizes processing and editing of 3D triangular meshes; CloudCompare has more functions for 3D point clouds initial data processing including clearing out noise, and merging and aligning multiple scans in test scans and the case study (Table 1-2)

Table 1-2: Point clouds processing software information

Company	Software	Price	Function
CloudCompare	CloudCompare	Free	CloudCompare is a 3D point cloud (and triangular mesh) processing software. It can be used to compare between two dense 3D points clouds or between a point cloud and a triangular mesh (CloudCompare, 2022).
Autodesk	ReCap	Free	Recap is an Autodesk spftware that helps designers and engineers capture high quality, detailed models of the real-world object (Autodesk, 2022).
	ReCap Pro	Paid	
Meshlab	MeshLab	Free	MeshLab is an open-source system for processing and editing 3D triangular meshes. It provides a set of tools for editing, cleaning, inspecting, rendering, texturing and converting mesh data, and making models for 3d printing (MeshLab, 2022).
Leica	Cyclone	Paid	Cyclone is a Leica Geosystem software that processes, models and manages 3D point clouds (Leica Geosystems AG, 2022a).
	Cyclone Cloud		Cyclone Cloud is a centralized, cloud-based version of Cylone (Leica Geosystems AG, 2022a).
	CloudWorx		CloudWorx is a digital reality plugins for AutoCAD systems (Leica Geosystems AG, 2022a).
	TruView		Share and view point cloud data freely via the web or desktop application (Leica Geosystem, 2022)
	Map360		Map360 is a software suite for building forensic investigation (Leica Geosystems AG, 2022a).
Faro	Scene	Paid	Faro Scene focuses on 3D point cloud capturing, data processing and registration (Faro, 2022b).
	As Built	Paid	Faro As Built is for CAD & BIM modeling and drawing (Faro, 2022b).

	BuildIT Construction	Paid	Faro BuildIT Construction is a complete design software solution for continuous construction verification (Faro, 2022b).
	BuildIT Metrology	Paid	Faro BuildIT Metrology is a quality control, tool building, guided assembly and machine alignment (Faro, 2022b).
	BuildIT Projector	Paid	BuildIT Projector planning, generating and operating laser projection projects (Faro, 2022b).
	Visual Inspect	Paid	Faro Visual Inspection helps access CAD data on a mobile device for fast visual inspection (Faro, 2022b)
Zoller + Fröhlich	LaserControl® Scout & Office	Paid	Z+F LaserControl provides a range of filters, measurement and registration tools that enables a high differentiate processing of scan data and are the key to filter, register and color 3D point clouds (Zoller + Fröhlich, 2022).
	SynCaT® - Mobile Mapping Software	Paid	Z+F SynCaT is a Mobile Mapping Software (Trimble, 2022; Zoller + Fröhlich, 2022)
Trimble	RealWorks	Paid	Trimble RealWorks are automated tools and point cloud specific workflows that allow users to import point cloud data from virtually any source, then quickly process, analyze and create high quality customer deliverables (Trimble, 2022).

1.4 Richard Neutra and Reunion House as a case study

As one of the greatest architects of the 20th century, Richard Neutra is famous for his international style practice in the United States. The Reunion House at Silverlake, Los Angeles, built in his later years, combines Neutra's signature architectural elements and was designed programmatically as a house with separate quarters for grandparents and grandchildred and a central meeting space (Lamprecht, 2021). The property is owned by the Neutra Institute for Survival Through Design and was designated as a City of Los Angeles Historic-Cultural Monument in 2021.

1.4.1 A Short biography of Richard and Dion Neutra

Richard Joseph Neutra (April 8, 1892 – April 16, 1970) was born in Austria and moved to the United States in 1923 at the age of 31. He grounded his life and career in Southern California and became a prominent modernist architect famous for suburban single-family houses. Studying architecture in Europe and working for Frank Lloyd Wright, Neutra developed his strong personal style by combining international style and the United States situation. For example, instead of using expensive materials, Neutra used wood structure and silver paint to mimic the appearance of metal (Los Angeles Department of City Planning, 2008).

Dion Neutra (October 8, 1926 – November 24, 2019) was Richard Neutra's son, a Modernist / International style American architect and consultant based in Southern California. Growing up in an architect family, Dion Neutra received training from his father at age 11. He then studied and graduated from the USC School of Architecture in 1950 (Lamprecht, 2021; Los Angeles Department of City Planning, 2008). After graduation, he worked in Richard Neutra's firm until 1965, when he became a partner. Following his father's death in the 1970s, Dion took over the leadership of the firm. On November 24, 2019, Dion Neutra died at his home on Neutra Place ("Reunion House") in the Silverlake neighborhood of Los Angeles at the age of 93 (Lamprecht, 2021; Los Angeles Department of City Planning, 2008).

1.4.2 Reunion House

Reunion House is a hillside residence built in 1950 and located at 2440 Neutra Place in Silver Lake, California, near Los Angeles. Richard Neutra designed the house to accommodate grandparents and visiting family members, hence the name Reunion House (Fig. 1-16) (Bahadursingh, 2021). The Neutra family bought the property in 1963. Three years later it was transferred to Richard's son Dion Neutra. (Bahadursingh, 2021). The house consists of a master bedroom, a living room open to the front garden, a guest bedroom for grandchildren, a study, two bathrooms, and a kitchen. The home is sited on a hillside and now hidden by abundant vegetation. An offset stair led visitors from the street to the front door. Alterations have been made by Richard and Dion Neutra based on needs over decades (Lamprecht, 2021). In 2021 Reunion House was added to Los Angeles City's list of Historic Cultural Monuments.

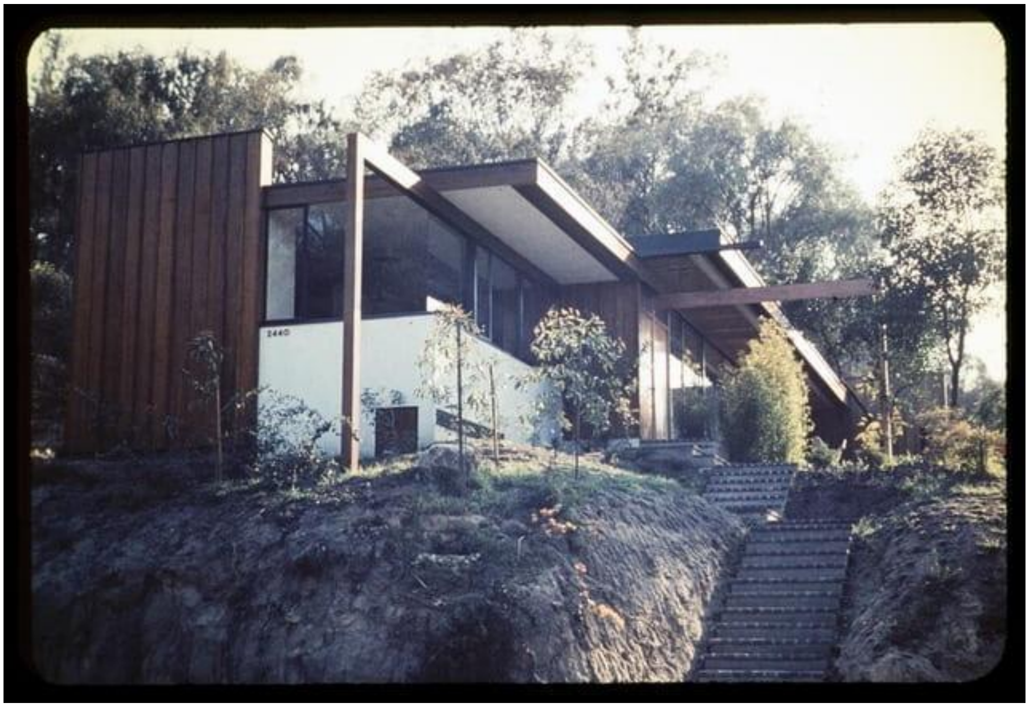


Figure 1-16: Reunion house, Silver Lake, Los Angeles, Calif., 1951 (Block, 1951)

The house is nominated as "an excellent example of a single-family dwelling in the mid-Century Modern architectural style, and a highly intact work by architects Richard and Dion Neutra" (Bahadursingh, 2021). Later the same year, a condition report and recommendation for the house was completed by a group of students from the University of Southern California.

1.5 Conclusion

Heritage conservation aims at preserving tangible and intangible cultural heritages. The discourse constructs two sets of heritage practices, one focuses on the management and conservation of heritage sites, places, and objects, and the other is related to the visitation of sites and institutions within tourism and leisure activities (Smith, 2006). In this process, investigations of both cultural and historic aspects and physical conditions are carried out. Surveys, documentation, preservation planning, preservation treatment, post-treatment documentation, maintenance monitoring, and public education in the investigation of the physical condition of the sites are considered conservation tasks. Among these tasks, scanning technologies can be appropriately used to assist with surveys, documentation, monitoring, and public education purposes.

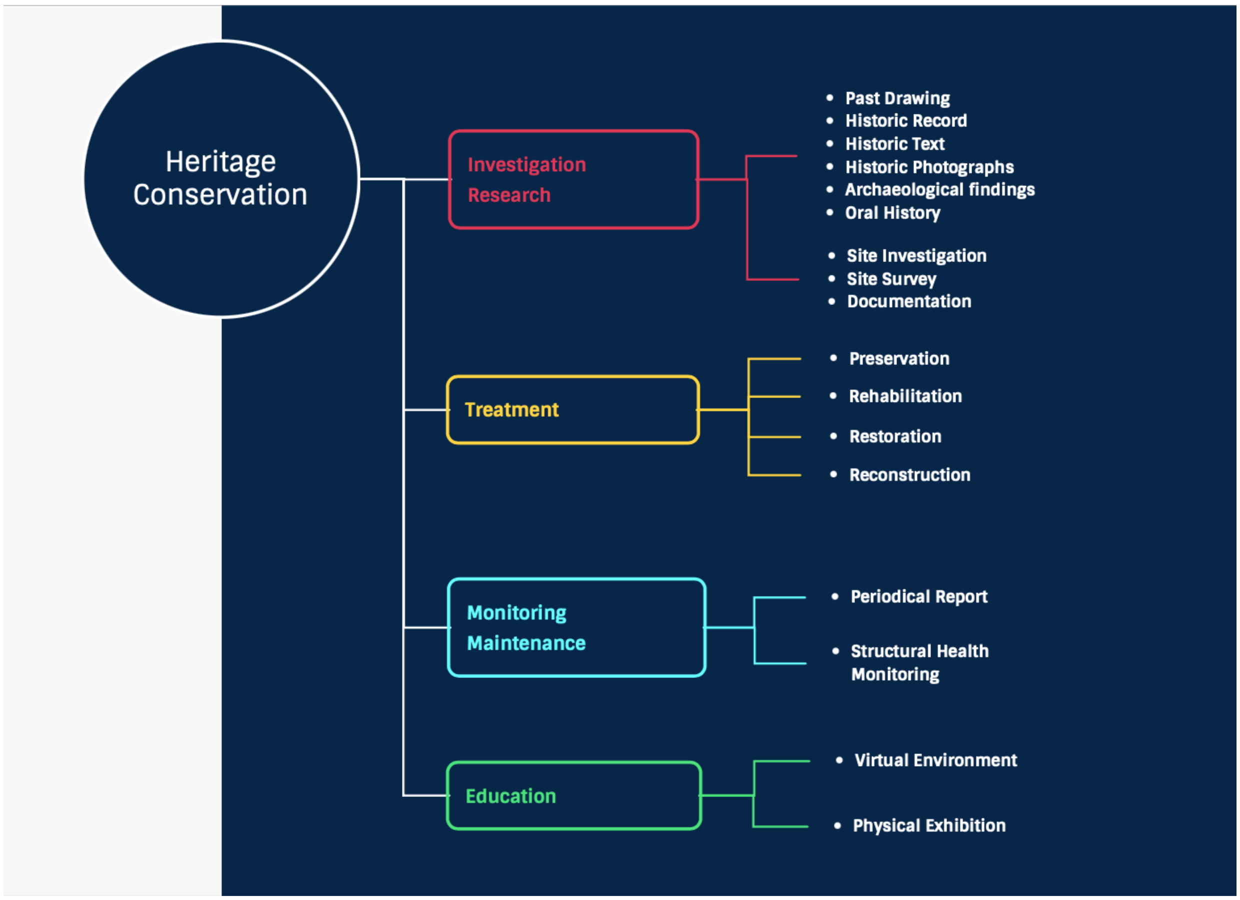


Figure 1-17: Heritage conservation task diagram

Scanning techniques were categorized types with visualization format and data acquiring procedures: 2D documentation including measured drawing and film, 3D photographs, and 3D scanning using different methods. Photographs with film medium or panoramic photos are typical 2D scanning, with a subcategorization of cylindrical and spherical panoramic photos. 3D spatial data can be captured through photogrammetry, structured light scan, triangulation scan, pulse scan, and Phase-Comparison scan, as well as Matterport and 360-degree cameras. Each of them has its strength and weakness, while a thoughtful combination of techniques can maximize the benefit and achieve a certain goal.

High accuracy, high resolution, and long range make professional 3D scanners favored by heritage conservation academia. However, considering the high cost of scanning by technicians and equipment, some organizations, individuals, and projects may not be able to afford when fundraising has long been an issue. Sophisticated data acquiring operations also place barriers for endangered heritage at inaccessible locations due to war or pandemic. Therefore, a hands-on and cost-effective scan method is needed. As smartphones began to be embedded with high resolution digital cameras and LiDAR sensors, spatial data acquired through 2D and 3D photographs, together with photogrammetry and LiDAR scanning can be provided by a portable and affordable smartphone or tablet (Figure 1-18). This alternative is waiting to be tested and workflow to be developed.

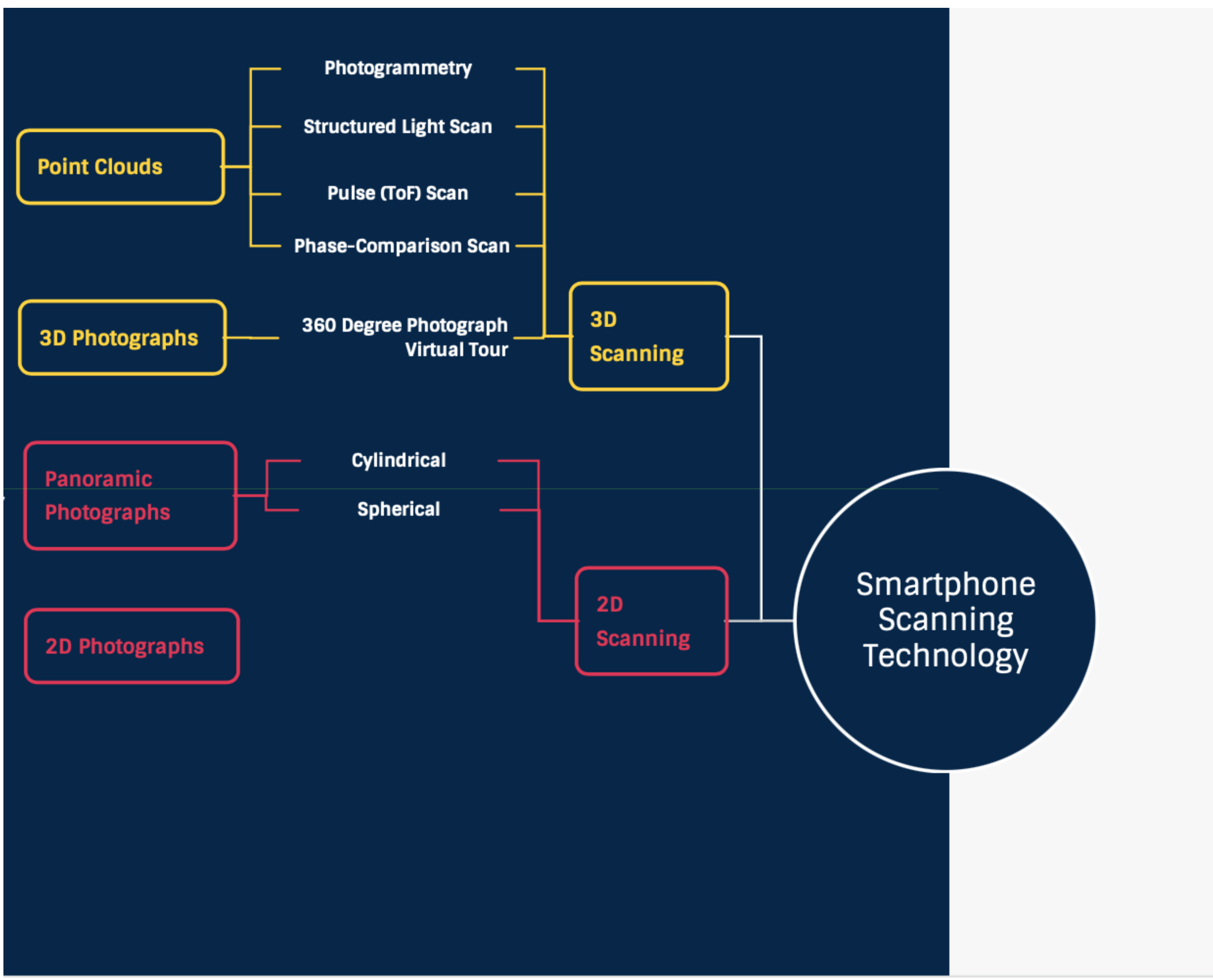


Figure 1-18: Smartphone Scanning Methods

Chapter 2. Literature Review

Advancement in science and technology has allowed scanning to be used in various industries; including but not limited to industrial manufacturing, medication, and large-scale ecosystem monitoring. In the field of Heritage Conservation, scanning is also widely used. 3D scanners work on different principles in acquiring 3D point data. Major types of scanners are triangulation, structured light, photogrammetry, time of flight (ToF), Phase-Comparison, and 360-degree photograph. Professional scanners' capability has been well evaluated with a significant number of past experiments and studies. Portable devices such as smartphones had only been studied in limited works of literature. The potential of using smartphone LiDAR sensors acquiring useful data shall be discussed. Available research, archive, city documents and a report on Reunion House are introduced at the end.

This chapter will describe 2.1 3D scanning's application in general fields of industry, 2.2 3D scanning's application in the field of Heritage Conservation, categorized with different working principles, 2.3 past studies using a smartphone for scanning, 2.4 past research and documentation done for Reunion House, and 2.5 summary.

2.1 Scanning for non-Heritage Conservation purposes

Scanning techniques perform their functionality in various industries. From object to terrain, 3D scanners work different principles such as triangulation, LiDAR, Phase-Comparison exhibit their limitation and strengths in field including industrial manufacturing, medication, ecosystem monitoring and etc.

2.1.1 Triangulation scanners application

Triangulation scanners work on the Law of Sin, which utilizes trigonometric triangulation of the angle and distance of light or laser to determine the location of a spot in three-dimensional space. Photogrammetry and structured light (Fig 2-1) are two most commonly used triangulation scanners; they have been applied in various scientific fields, such as industrial manufacturing (Ikkala et al., 2022; Karganroudi et al., 2023; Siwiec & Lenda, 2022), ecosystem monitoring (Hirtle et al., 2022; Mineo et al., 2022; Nasiri et al., 2022; Rodríguez et al., 2022; She et al., 2022; Strunk et al., 2022; Ternon et al., 2022; Wang, 2022; Whitehead et al., 2022; Zhang et al., 2022), urban planning improvements (Taniguchi et al., 2022), medication (Douglass, 2022; Lauria et al., 2022; Shao et al., 2019; Shao et al., 2022), and anthropology studies (Garashchenko et al., 2022). Photogrammetry is a scanning method relying on software calculation with 2D images; Structure Light scanning is an on-site scanning approach with projected patterned light onto surfaces. Both photogrammetry and structured light scanning work on trigonometric triangulation.

Figure 2-1: Structured Light Scanner (Lievendag, 2017)

There are reports on applying photogrammetry in the modeling of forest canopy cover as various ecological parameters of forest ecosystems (Zhang et al., 2022). The authors found that the integration of photogrammetry, Sentinel-2 data, and ML models can optimize the generation of landscape-level scale maps in a precise and fast fashion (Zhang et al., 2022). Ternon et al. focused on the possibility of using photogrammetry to map the rocky reef under turbid environments. Combined with RGB, DSM, and several spatial benthic terrain variables, the methodology of mapping through triangulated data provides new perspectives to understand the relationships between the reef rock and benthic organisms(Ternon et al., 2022). Both works of literature proved that photogrammetry can generate three-dimensional geometrical data at a topography scale, even in unclear situations.

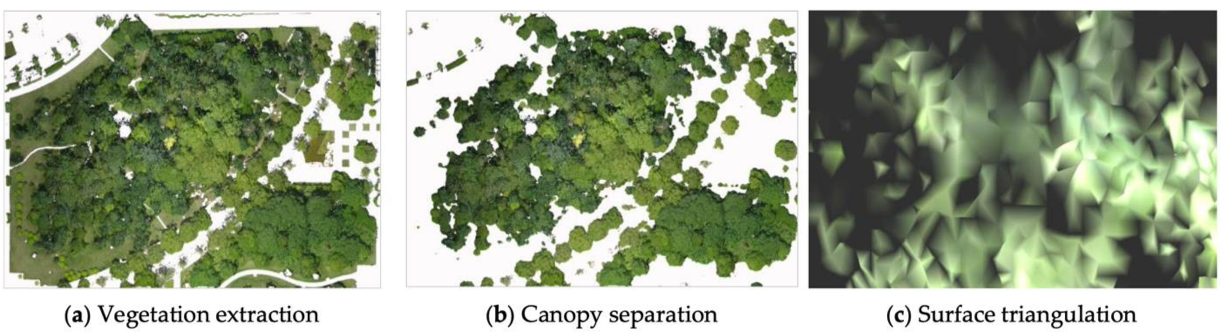


Figure 2-2: The three major processing steps of PCs. (a) The vegetation was extracted by using SVIs. (b) Grass was separated from the canopy using CSF. (c) The separated canopy PCs were triangulated using Delaunay triangulation. (Zhang et al., 2022)

Not only used for ecosystem analysis, triangulation scanning is also used for improving urban living environments. Triangulation scanning was used by a group of Japanese scholars to digitally reconstruct sidewalks. Subtle undulations and elevations can be detected from the digital twin generated from the collected photographs, thus improving disadvantaged groups' urban living experience (Taniguchi et al., 2022). In industrial applications, triangulated data improves molding manufacturing workflow, reducing deviation and optimizing innovative maintenance systems (Karganroudi et al., 2023; Vizzo et al., 2022).

In museum settings, triangulated surface models by Structured Light scanning are used to digitally construct a fossil skull in order to compare the difference between the object, point cloud scanned model, and the CAD-built model (Garashchenko et al., 2022). Photogrammetry and Structured Light scanners were compared to computer tomography (CT) scans in medical science. The research revealed that both techniques cannot provide internal structure information; the requirement of multiple scans or perspectives is also time-consuming. The literature noted that both optical scan methods performed well within great detail. It also mentioned the trend of using smartphone light detecting and ranging (LiDAR) for cost-effective and daily operation purposes (Douglass, 2022).

As these works of literature exhibited, photogrammetry is able to provide an overview of large research areas and small object details. Equipped with mobile and aerial devices, photogrammetry can also be used in inaccessible locations. While under conditions such as wind, clouds, or hazy weather aerial photography can be affected in process and quality. With a canopy or partially covered terrain or surface, photogrammetry is unable to generate data beneath the canopy. Structure from light scanners, which also work on triangulation calculation, has a better performance in a well-controlled dark indoor environment than in bright exterior space.

2.1.2 LiDAR scanners application

LiDAR is the abbreviation of “laser imaging, detection, and ranging” (Taylor, 2019). With a beam of laser travel from scanner to object and comeback, the distance can be measured with time taken in the roundtrip.

Figure 2-2 : Faro Focus Laser Scanner (Faro, 2022)

LiDAR takes the advantage of the strong energy emitted with every single beam of laser, allowing scanning over a long distance. Equipped with a tripod or a drone, LiDAR scanners are commonly categorized into Terrestrial Laser Scanning (TSL) and UVA. Long-range TSL scanning can reach up to 6 kilometers range. In 2019, Riegl VZ-6000 scanner was used to measure the annual mass balance of a Glacier (Xu et al., 2019). Large outdoor environments (Vizzo et al., 2022), forests (Sofia et al., 2022), and cities (Setyawan et al., 2022) are scanned with a pulse LiDAR system for management, visualizing, and modeling purposes. The strong energy embedded in the laser beam is able to reach the ground through the vegetation canopy. Even though a filtering process is required, LiDAR scanners enable the possibility of scan the ground surface without bushes, hedges, and trees, placing the technology at advantage comparing to triangulation scanners (Gitbook, 2022).

Figure 2-3: LiDAR drone concept. (www.microdrones.com)

Beyond scanning from great distances, LiDAR is also used in industrial diagnosis (Gargoum et al., 2022; Jovančević et al., 2017; Shu et al., 2022). Researchers used LiDAR system to analyze collision data for roadside safety assessment purposes. LiDAR laser system was implemented in welding equipment in improving manufacturing performance with its high accuracy and precision (Shu et al., 2022). Sharing the same purpose of high-accuracy measurement, airplane exterior defects detection also made use of LiDAR systems (Jovančević et al., 2017).

LiDAR scan technologies utilize lasers, which are commonly used for tide analysis or shallow clear water submarine environment reconstruction, due to water absorption (Filisetti et al., 2018; Zhou et al., 2021). Key factors impacting LiDAR signal in the marine environment were examined; the range of laser transmission was determined as over 35 meters in clean seawater, The transmission distance less than 20 m in coastal seawater and the transport distance in turbid port water was approximately 5 m (Filisetti et al., 2018).

Since 2020 when Apple released their iPhone 12 Pro and iPad Pro, which are equipped with LiDAR, a rising trend in academia began to test its capability of scanning. Studies have been performed in the area of geoscience (Bharadwaj et al., 2022; Tavani et al., 2022), transportation monitoring (Wang, 2022), and ecosystem (Holcomb, 2021). The user-friendly communication design and rapid scan and processing speed were acknowledged by researchers, proving the possibility of replacing professional scanners under certain conditions (Holcomb, 2021; Wang, 2022). To evaluate its capability, the quality of captured data from smartphones was assessed and compared with established ground-based 3D scans (Spreafico et al., 2021).

Figure 2-4: iPad mounted on tripod, testing static configuration (Spreafico et al., 2021)

2.1.3 Phase-Comparison scanners application

A Phase-Comparison scanner projects constant waves of infrared light of varying length, by receiving reflected waves from object surface; the difference between wavelengths is used to generate shape information (Fig. 2-3) (Daneshmand et al., 2018).

Figure 2-5: Phase Comparison Scanner (Faro, 2022a)

Several applications of Phase-Comparison scanners have been proposed in ecological monitoring, some focusing on tree canopy (Stanley, 2013), and others on tree metric measurement (Pueschel, 2013). It was reported in the literature that the maximizing of sampling efficiency can be achieved with low scanning time. However, high accuracy can result in the requirement of merging multiple scans to achieve a certain volume (Pueschel, 2013). Phase-Comparison scanners are also used in crime analysis (Esaias et al., 2020). A Faro scanner was used in comparison with the manual method of estimating bloodstain origin. It validated the practical benefits of 3D scanning and reliability in BPA reconstruction documentation for technical review and court presentation (Esaias et al., 2020).

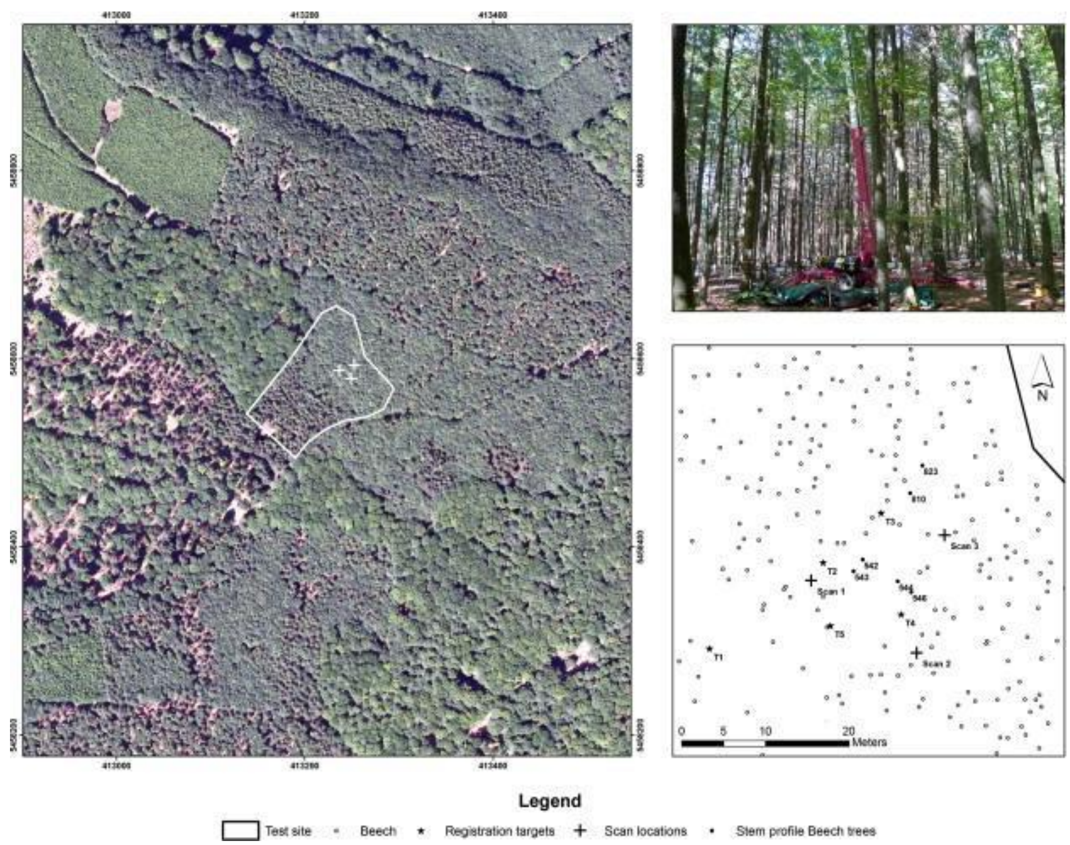


Figure 2-6: Phase-comparison scanner scanned image (Pueschel, 2013).

2.2 Scanning heritage

Scanning heritage not only provides documentation for the site or property, it is also the base of the entire planning work. Panoramic photos, triangulation scans, photogrammetry, structured light scan, LiDAR scans, and Phase-Comparison scans can all be combined and applied to benefit the field of heritage conservation.

2.2.1 Panoramic photo application in Heritage Conservation

Panoramic photo is a quick and low-cost acquisition method that stitches photographs to a view up to 360 degrees with no distortion or aberration (Shum & Szeliski, 1999). With computer software and distance meters, a panoramic photo is valued with geometric information (d'Annibale et al., 2013). The medium has been implemented in the workflow of creating virtual architecture (d'Annibale et al., 2013). Panoramic photographs were practiced with structure from motion and multi-image spherical photogrammetry techniques in producing virtual reality tools and proved their ability in reconstructing virtual scenarios (d'Annibale et al., 2013).

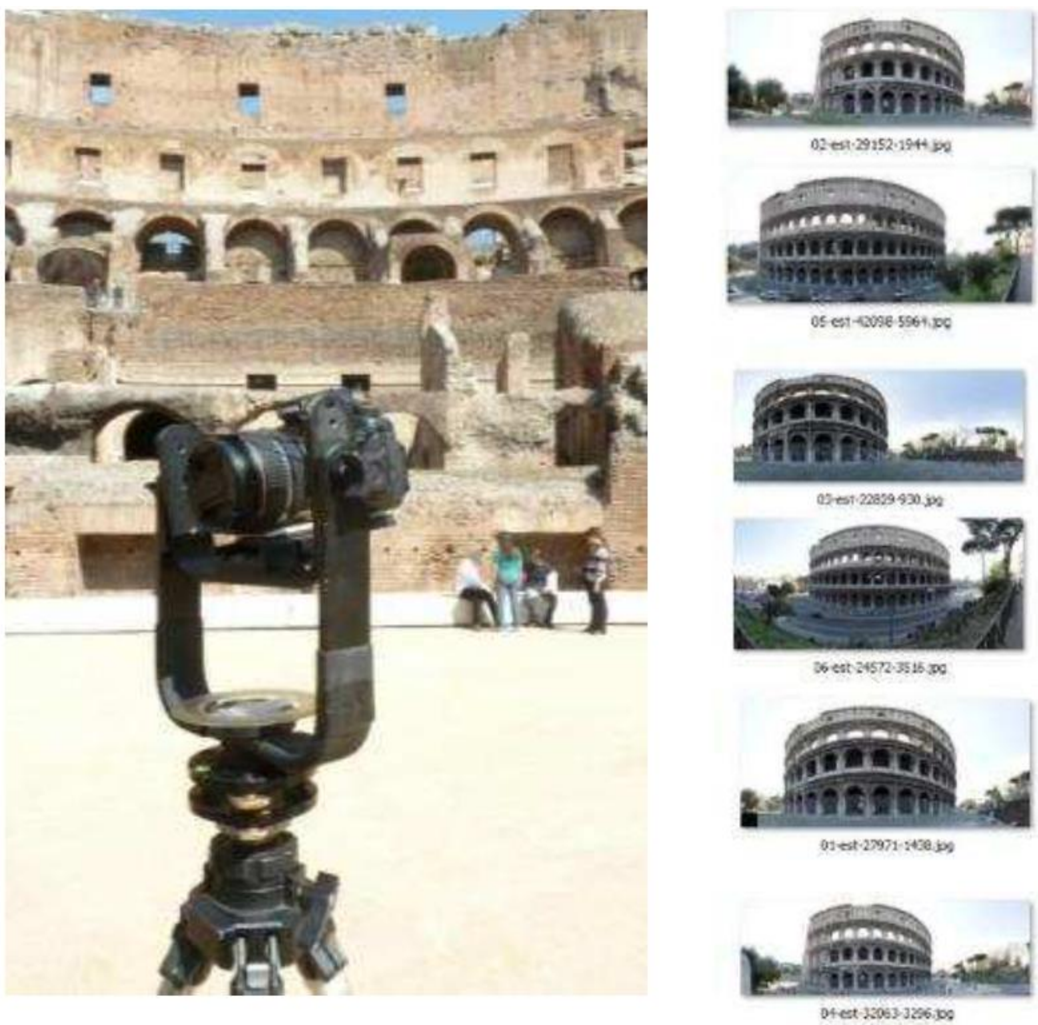


Figure 2-7 Panoramic photographs of the Colosseum in Rome (d'Annibale et al., 2013).

Similar research had also been done in revealing the promising ability of panoramic photographs when working with spatial data obtained from TSL scanners (Salemi et al., 2005). Several historic buildings in Europe were captured and transformed into web-based animation through a computation process that joined panoramic photographs and point clouds (Salemi et al., 2005). The result supported its economic and effective performance as being better than the computational modeling of indoor space (Salemi et al., 2005).

2.2.2 Triangulation scanners application in Heritage Conservation

Triangulation is one of the most widely used methods to acquire spatial data from architectural features. Scanning techniques work on triangulation including photogrammetry and structured light scanners.

2.2.2.1 Photogrammetry application in Heritage Conservation

Recent research in photogrammetry has primarily focused on monitoring changes in built heritage sites (Liu et al., 2022; Vellanoweth et al., 2022), examining large-scale historic resources (Harbowo et al., 2022; Simek et al., 2022), assisting visual ability under hostile conditions (Grifoni et al., 2022), and documenting museum objects (Romano et al., 2022). Activity is growing to address the broadened uses of photogrammetry in the field of Heritage Conservation. Photogrammetry-generated models enable the visibility of structures and subjects at extremely close distances, and in difficult conditions for human eye perception (Grifoni et al., 2022). In 2022, a group of scholars reviewed a wall painting using photogrammetry on a narrow steel walkway, which restricted the view of the mural to extremely short distances (≈40 cm) that makes general viewing difficult (Grifoni et al., 2022). Photogrammetry is also applied in generating orthoimages of wall paintings. With a large lateral overlap ratio between abutting shots, photogrammetry technique allows the undistorted view of the surface in hostile fruition contexts (Grifoni et al., 2022). In the same year, the photogrammetry technique assisted researchers to examine the relationships among glyphs and their physical contexts in ancient caves and see images that were otherwise invisible during in-person observation (Simek et al., 2022).

Figure 2-8: Orthoimage of mural painting by photogrammetry (Grifoni et al., 2022).

In surveying current literature of photogrammetry scan of historic resources, scholars generated spatial data with a variety of image sources. This source is not limited to photographs taken by professional cameras (Attarian & Safar Ali Najar, 2022; Simek et al., 2022), crowdsourced images (Liu et al., 2022) and videos (Vellanoweth et al., 2022). are also available for generating data with resolution that is high enough for specific research purposes. On the upper Gulf of California, México, photogrammetry generated from videos taken at different times was used to evaluate the erosion trend of heritage in the coastal environment (Vellanoweth et al., 2022). The resolution has been proved largely related to the numbers of photos taken, resolution of photographs, and lateral overlap between contiguous pictures (Grifoni et al., 2022; Simek et al., 2022; Vellanoweth et al., 2022). Various choice of image sources for photogrammetry also led to consideration towards cost-effective concerns in the HP domain. The historic facade of Bothwell Castle in Britain was monitored through pictures taken by a vast number of tourists. Scholars suggested the potential of producing small-scale digital reproduction of historic sites through crowdsourced image photogrammetry instead of massive scale projects that increase unnecessary costs (Liu et al., 2022). Comparison between laser scanning and photogrammetry in HC practice was carried out; photogrammetry showed its strength in capturing data with complex geometric shapes, creating dense and textured point clouds, and cost-effectiveness that fit better into the HP reality than professional laser scanners' heavy equipment, high cost, and lack of adequate surface coloring (Alshawabkeh et al., 2021).

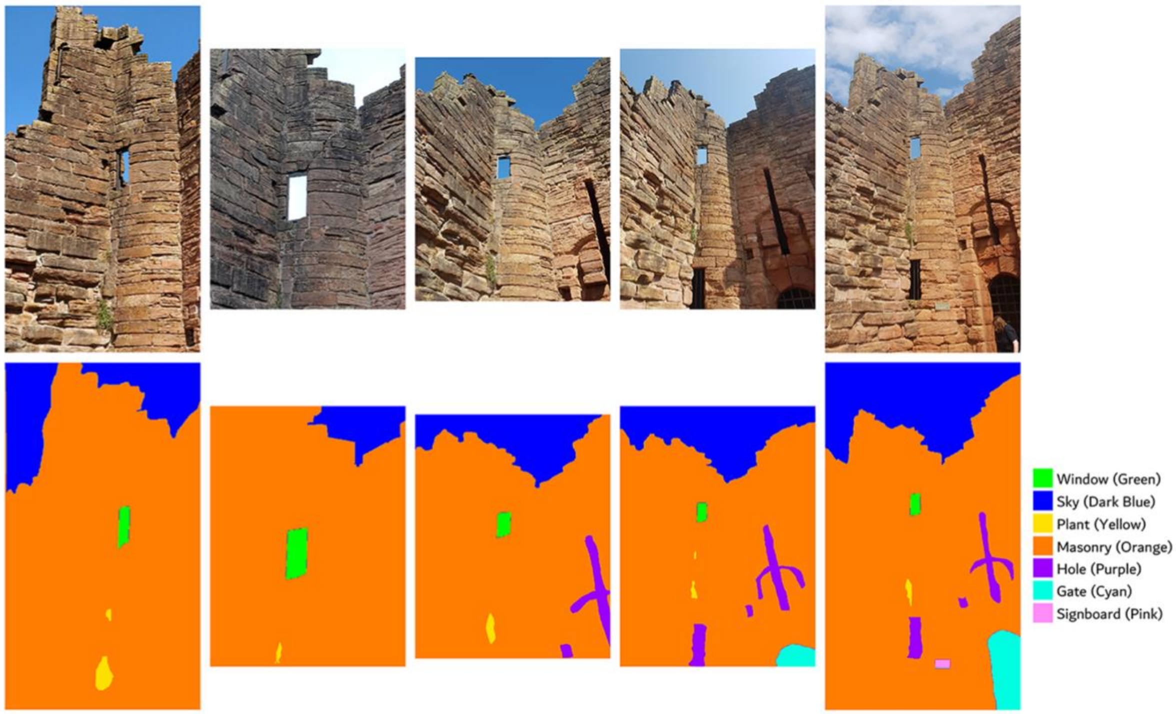


Figure 2-9 Photogrammetry from crowdsourced photography (Vellanoweth et al., 2022).

2.2.2.2 Structured Light application in Heritage Conservation

Structured Light scanners are widely applied in cultural artifacts and relics scanning. Recent literatures reviewed its capability in historic fabric (Montusiewicz et al., 2021), artworks (Sánchez-Jiménez et al., 2019), artifacts (McPherron et al., 2009; Rocchini et al., 2001) and architectural features (Arias et al., 2005; Patrucco et al., 2019). Back in 2001, researchers developed a low-cost scanner with a Structured Light system fulfilling HP interests in completed shape and requirements on accuracy (Rocchini et al., 2001). Its valuation of different patterns, scanner calibration, and color acquisition ability were thoroughly studied and examined; the result shows the limited range for a single scan led to longer scanning time (Rocchini et al., 2001), which was also noted in later scholarly work at two Middle Paleolithic sites in southwest France (McPherron et al., 2009). The range covered for a single scan is determined by light emitter's range and acquisition volume of the receiver. Even multi-station scans can be registered to acquire large-scale objects or scenes (Shao et al., 2019), recent research with the application of Structured Light scanners exhibited a trend on relatively small objects compared to village, district, and city scale scanning.

Figure 2-10: Structured light scanning on the Minerva case study (Rocchini et al., 2001).

In the most recent studies, scholars used structured light scanners in developing measurement system assisting cultural relics packaging process (Shao et al., 2019), exhibiting historical cloth (Montusiewicz et al., 2021), and testing its precision on oil painting (Sánchez-Jiménez et al., 2019). Structured light scanners' limitation in small scanning range and multi-station scan was overcame through overlaid with one TSL scan of the entire grotto. The combination saves time and energy at the same time and provides accurate and detailed spatial data (Shao et al., 2019). The improvement and study of Structured light scanners surround the cost-effective concerns (Rocchini et al., 2001; She et al., 2022).

2.2.3 Light Detecting and Ranging (LiDAR) application in Heritage Conservation

LiDAR is an acronym for "light detection and ranging." It works by calculating distance from the time difference between the laser beam being shot out and received. Pulse scanners and time of flight scanners work in the same way. LiDAR scanners are the most commonly used 3D scanners for their ability to acquire data in one scan, especially for large scale projects (Shao et al., 2019; Vavrouchová et al., 2022). The working principle of emitting a single pulse of laser beam with strong energy enables LiDAR scanners to acquire data from great distances. Equipped on a drone, LiDAR scanners complete the scanning of a village from the air (Vavrouchová et al., 2022). Researchers studied the depopulation and abandonment of rural mountain villages in post-World War I Europe (Vavrouchová et al., 2022). Ownership boundaries of land can be clearly recognized through the LiDAR point clouds; large remnants of buildings were detected not as ground but as buildings in LiDAR-derived DEM systems (Vavrouchová et al., 2022). Researchers compared LiDAR-scanned villages to archival cadastral maps and field survey, and concluded that it is the best choice in "detecting ancient ploughing patterns, concealed under both tree canopy and turf." (Vavrouchová et al., 2022)

In the field of historic preservation, LiDAR system has also been used for reconstructing heritage sites and artifacts digitally (Bent et al., 2022; Shang & Wang, 2022), documenting (Yastikli, 2007), cultural resource management (Daly et al., 2022), improving public education experience (Ballarin et al., 2018), and evaluating technical condition of buildings (Nowak et al., 2020; Özeren & Korumaz, 2021). Ground-based LiDAR systems, also known as Terrestrial Laser Scan (TLS) shows usefulness in building diagnostics (Nowak et al., 2020). Researchers obtained geometrical data of a whole building including staircases and basement with Faro Focus M70. Wall distortion and large floor deflections were diagnosed by analyzing point cloud data and drawings. Nowak, et al., concluded that TSL scans can effectively assist diagnostics of physical conditions, and determine the cause of damage of a building (Nowak et al., 2020). In Özeren and Korumaz's 2021 study, point clouds acquired from a structure by a Faro S120 Laser Scanner were further processed and analyzed with registral and design software into HBIM (Özeren &

Korumaz, 2021). LiDAR and HBIM are proven to make valuable contributions to historic preservation decision-making (Özeren & Korumaz, 2021).

Figure 2-11: TSL scanned data in Autocad measuring deformation of front wall (Nowak et al., 2020).

However, LiDAR scanners have certain limitations in unfavorable weather conditions, vibrations, and reflective surfaces (Filgueira et al., 2017; Nowak et al., 2020). Its poor performance in rainy conditions has been demonstrated by a variation up to 20 cm in the worst situation. Reflective surfaces, translucent and opaque objects also cause false or missing points in the scan (Haddad, 2011). Scan data can be improved through covering the surface with a thin layer of white powder with an approximately 45-degree angle (Alshawabkeh et al., 2021; Haddad, 2011). Recent studies on Longmen Grottoes explored the possibility of overlaying a TSL scan with a Structured Light scan to reach high accuracy, large range, and high scanning speed at the same time (Shao et al., 2019).

Stating the concern on registration process, high-cost, and large equipment of TSL scanners, (Alshawabkeh et al., 2021), scholars' interest in LiDAR's application in HP is leaning towards utilizing cost-effective alternatives (Gonçalves et al., 2019; Murtiyoso et al., 2021). A first assessment of smartphone LiDAR in the historic preservation domain was tested in 2021. Researchers examined the solid-state LiDAR (SSL) embedded in Apple products in three case studies, comparing scanning results with TSL and DSLR photogrammetry data. It proves that SSL is capable of scanning for 3D visualization, AR, VR, while unsuitable for tasks which require higher precision such as detailed 3D printing, digital twins, HBIM, orthophoto, texture analysis, and mesh analysis. The authors also pointed out that future research on assessing SSL in large selection of sample objects should be carried out (Murtiyoso et al., 2021).

2.2.4 Phase scanners application in Heritage Conservation

A large number of existing studies in the broader literature have examined phase-comparison scanners' ability to obtain dense point cloud data (Fais et al., 2019; Fais et al., 2017) and, more specifically, detect deficiency of surface and complex objects (Fais et al., 2017). It was reported in a study of the complex shape of some artifacts from the “Palazzo di Città” monumental compound that long-range phase shift terrestrial laser scanners (Leica HDS-6200 TLS) are able to generate an extremely high density of point clouds with multiple scans (Fais et al., 2017). Determined by its working principle, Phase-Comparison scanners (PS) exhibited strength in detecting defects in the surfaces of walls (Suchocki, 2020). It has been used with ultrasonic tomography for detecting internal defects and heterogeneity of a comenditic pyroclastic rock and Pietra Forte carbonate rock samples (Fais et al., 2019).

PS scanners work on emitting laser lights that are modulated in specific waveforms. Once laser light reached the surface of the object, the intensity pattern is displaced by the impact on the surface of the object. Measuring the differences between the outgoing and receiving laser signals provide precise distance calculations. Recent PS scanners are proven to provide sufficient accuracy under the condition of an angle exceeding 70 degrees with approximately 80% data loss (Mill, 2020), which is considered accurate, fast, and provides high-resolution data (Faro, 2022c). At the same time as achieving fast and denser data set, phase-based scanner is noisier with limited range. Limited by its working principle, PS scanners are strongly impacted by tree canopy, and reduced accuracy in more dynamic range (Geo Week News Staff, 2004).

2.2.5 360 Degree photograph application in Heritage Conservation

360-degree photography is generated from photographs taken at one location from different angles (Panoraven, 2021). It provides a full spherical view of an observer standing at one point looking in different directions (Panoraven, 2021). The 360-degree photographic technique was practiced with laser scanning technology in supporting conservation design -in Portugal and a Romanesque church in Spain (Masciotta et al., 2023). Heritage conservation groups also make use of 360-degree photographs for representation.

Figure 2-12: 360 degree panoramic photographs linked to BIM for heritage conservation (Masciotta et al., 2023)

A series of 360-degree photographs can be joined in a 360-photograph virtual tour. In a virtual tour, instead of viewing from a single standpoint, users can move between different photo shoot locations and experience space. (Fig. 2-4). A past web-based research had been done at the Municipal Baths of

Strasbourg. Scholars took series of photographs and stitched them into 360-degree views of various location within the baths, an interface was then created allowing audiences to pass by using a transition from one panoramic image to the next one (Koehl et al., 2013). In-depth workflow of planning and creating virtual tours were discussed in literatures focus on cultural heritages. The research for the historic centre of Rethymno virtual tour creation brought a 360-degree photographic virtual tour into a game engine and Virtual Reality to increase its immersive interactivity (Argyriou et al., 2020). 3D visualization of cultural heritage in Caceres, Spain, combined 360-degree photographs and TSL scanning into a hypermedia atlas through a web-page. Point clouds acquired by TSL scanners were used to make up for 360-degree photographs' limitation in spatial data, increasing the data obtained in this hypermedia atlas (Naranjo et al., 2018).

Figure 2-4: Michael White Adobe presented by AQYER (A Friends of the Michael White Adobe, 2022)

2.3 Studies using a smartphone for scanning

With a LiDAR system attached to smartphones, scanning with portable devices is an accessible approach for an average person. Serving heritage conservation objectives with smartphone devices is of high interest for its speed, portability, and cost-effective considerations which are not easy to meet with high-end scanners (Spreafico et al., 2021). Past research suggests that the LiDAR system embedded in iPhone products are solid state LiDAR (SSL), which “creates a fine grid of points, with the distance to each point measured individually"(Murtiyoso et al., 2021). The spatial tracking ability of Apple products was evaluated for the purpose of Augmented Reality (AR). At a 50 m distance, Apple products had a precision at around 1.2 m, and accuracy at around 1.8 m-1.9 m range (vGIS, 2020). Further research on Apple product scanners tested the ability of 3D rapid mapping and its quality (Spreafico et al., 2021). The research indicated that the SiteScape app constrains the maximum size of the scanning file, which led either to a longer scan with a lower density or increasing density limited to a smaller area (Spreafico et al., 2021). The accuracy of tested data were compared using the ICP algorithm in Leica Cyclone 3DR (Spreafico et al., 2021). Cloud-to-cloud distances analysis suggested that edited iPad Pro scans can reach 67% of points within 2 cm from the ground truth scan by the TSL scanners (Spreafico et al., 2021). The evaluation led to a conclusion that point clouds obtained from Apple products with LiDAR sensors are suitable for 1:200 map scale based on Italian standards (Spreafico et al., 2021).

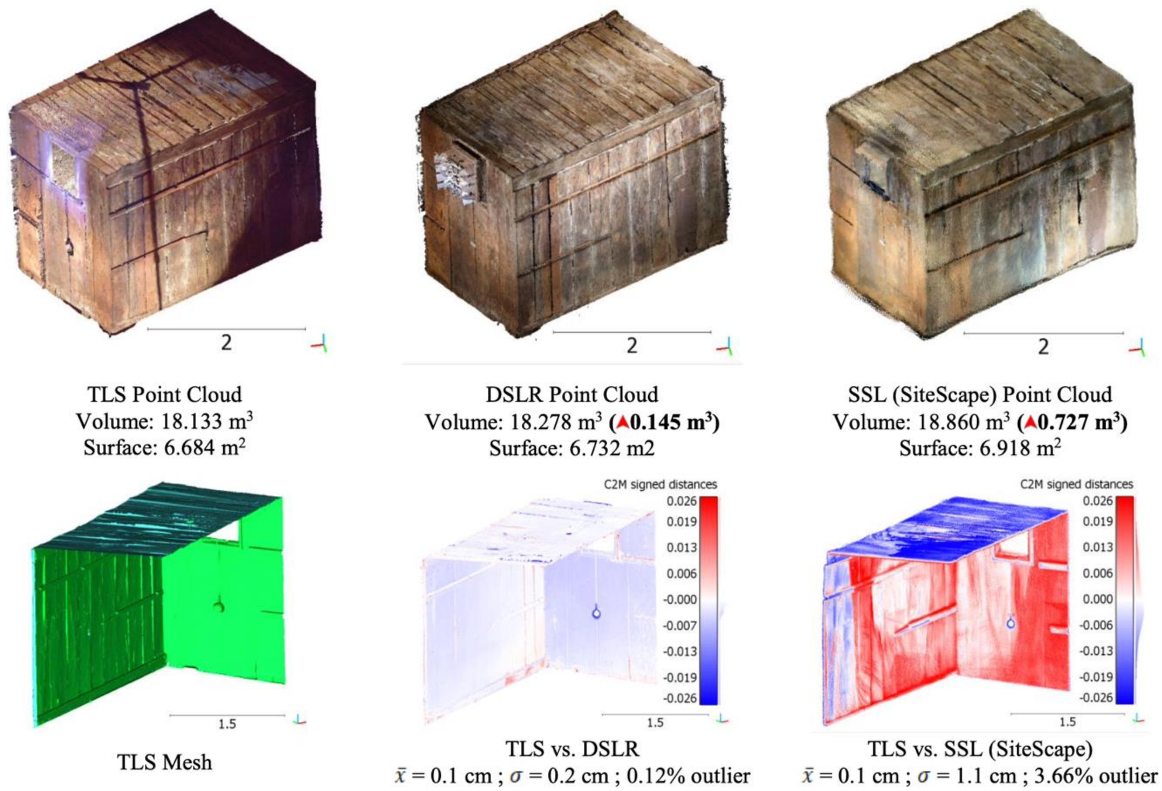


Figure 2-12: Data comparison with TLS, DSLR, and SSL (smartphone) (Spreafico et al., 2021).

2.4 Existing research on Richard and Dion Neutra's Reunion House

Built in 1951, the Reunion House was programmed and designed as a place where grandparents and grandchildren can sleep separately but share common living spaces. The house underwent a series of alterations based on Richard Neutra's son Dion Neutra's needs when lived on the property. The Reunion House was listed as a City of Los Angeles' Historic Cultural Monument in 2021.

Character-defining features (CDFs) contribute to the significance of the house; they are also the key elements to be documented and conserved within the whole context of the building. Exterior and interior CDFs are identified in the designation application. In addition to documents provided available from the City of Los Angeles, a group of students from University of Southern California produced an assessment and recommendations report and presentation for the property in 2021.

2.4.1 Reunion House developmental history (Lamprecht, 2020)

Arthur L. Johnson, Jr. commissioned Richard Neutra to build a single-family house after he purchased the lot at 2442 Neutra Place on Sept. 27, 1949. A permit was issued from the City of Los Angeles Department of Building and Safety for a “New building permit for home 34’ x 91’” after a year of design. In the following year 1951, Johnson Jr. received his Certificate of Occupancy and was able to move into the property. The Johnsons, sold the property to Alphonse D. Makowski and Ann L. Makowski. in the following year. On May 2, 1962. The house owners sold the property to William Hobson and Evelyn T. Hobson. In 1963 Dion Neutra bought the property from William Hobson and Evelyn T. Hobson and began a series of alterations based on his understanding and needs. A reflecting pool adjacent to the west elevation of the building was added in 1964; interior features such as shelving and mirrors next to the fireplace, as well as the kitchen curtain were added at the same time. In 1966, the kitchen was remodeled and brown-stained concrete in the living room was carpeted. Additional alterations including the exterior walls, interior lighting systems, and restoration of the ceiling to the original wood finish had been completed by Dion Neutra between 1966 to 1968. In the bedrooms, Dion Neutra added shelving, a closet, a desk unit, and lighting according to his needs. Behind the master bedroom, Dion Neutra added a closet addition for his wife. In 1968, Dion Neutra decided to add a second floor to the garage based his father, Richard Neutra’s original drawing for Arthur Johnson. In order to accomplish it, Dion Neutra reinforced the structure to support the unit above the garage and added a driveway for the renter’s vehicle. At the rear of the house, a retaining wall was also added. These alterations are considered significant because they were designed by Richard Neutra’s son, Dion Neutra during the period when the house took the form that exists today.

2.4.2 Reunion House Character Defining Features

As a case study example for the smartphone’s ability to meet heritage conservation objective, Reunion House’s Character Defining Features (CDFs) are key elements to be scanned within the whole building entity (Table 2-1).

Table 2-1 : Exterior Character-Defining Features (Lamprecht, 2020)

<table>
<tr><th>Exterior Character Defining Features – Mid-Century Modernism</th><th>Exterior Character Defining Features – Neutra</th></tr>
<tr><td>a long, horizontal profile reinforced with a flat roof</td><td>use of stucco walls contrasted with casement and fixed windows and sliding window walls, to effect an aesthetic of alternating solids and voids</td></tr>
<tr><td>a deep integration with site, setting, and landscape through extended overhangs copious amounts of glass materials that continue from inside to outside, bridging interior and exterior</td><td rowspan="3">use of paint – white, dark brown, and here, silver (common to Neutra’s window frames, posts, and sills) and grey. These colors were used in order to project (white) or suppress them or make them recede (brown.) Based on Gestalt aesthetics, this is an additional strategy specific to Neutra to introduce another kind of “solid-void” relationship. Silver (actually aluminum) paint was used both to protect rust-prone steel and to “dematerialize” window frames or his 4”x4” wood posts for a more uninterrupted view to nature, based on Neutra’s knowledge of evolutionary biology and the African savannah.</td></tr>
<tr><td>post-and-beam construction, or the regular disposition of posts</td></tr>
<tr><td>diagonal views through mitered glass corners or through simple, minimal vertical member at corner</td></tr>
<tr><td>windows usually sliding, casement, jalousie, or fixed lights, with simple frames that appear commercial in origin</td><td>projecting beams extending beyond the building envelope, either floating free, or terminating in a post as a “spider leg”</td></tr>
<tr><td>doors are usually single-panel wood or painted, with no ornamentation or elaborate detail</td><td rowspan="2">deep overhangs, often with strip lighting flush with overhang and at its edge. rounded post caps, created by adding a separate piece of lumber, flat on one side and subtly rounded on the other, which fit over a squared 4’ – 4”, thus softening the visual effect of an otherwise rectilinear composition</td></tr>
<tr><td>use of simple, modern materials: concrete, stucco, float glass, steel, and aluminum, contrasted with natural materials such as brick and stone, either random or ashlar cut</td></tr>
<tr><td>a rhythmic distribution of details, wall treatments, textures, and windows. lack of applied ornament</td><td>reflecting pools adjacent to the house to reflect nature post</td></tr>
</table>

2.4.3 Documentation techniques used previously on Reunion House

The Reunion House is currently under Neutra Institute ownership and stewardship. Past scholars studied the history of the house from its past to today. City survey documents, archival photographs, interviews with Dion and Richard Neutra, site maps, periodicals, books, and various materials are available for study and reference. The documents are mostly hand drawn design and construction documents on paper or film based.

In 2021, Reunion House was listed as a City of Los Angeles Historic-Cultural Monument. The official agenda package for designation includes the Final Determination Staff Recommendation Report, Categorical Exemption, Under Consideration Staff Recommendation Report, and Historic-Cultural Monument Application. Brief introduction, general information, and California Environmental Quality Act (CEQA) findings are discussed in Final Determination Staff Recommendation Report. The report determined that the Reunion House meets criteria 1) be identified with a significant event, 2) be associated with important people, 3) embodies the distinctive characteristics of a style. In the report, an architectural description is included. The piece of writing detail documented the building's relationship to the tract, direction, size, and major components of the structure (see Appendix B) (Lamprecht, 2020). Then each elevation was elaborately described. In Lamprecht's report, the physical appearance and the notion of Neutra's architectural design was pictured through written expression. While A verbal description of a building is simply not enough to properly capture the essence of the structure. A 3D scan of the building is necessary to accurately represent its size, scale, and dimensions, as well as its three-dimensional qualities such as its structure, design, and composition. A 3D scan can be used to document a building or structure in ways that words alone cannot achieve. It captures the three-dimensional quality of architecture and space, allowing viewers to see the building from different angles and perspectives. A 3D scan can also provide the exact dimensions and scale of a building, providing a clear idea of its size and layout. In addition, scans can be used to document the building in case of its destruction or loss. It can also be used to track changes in a building over time, allowing for an examination of the evolution of a structure. Finally, 3D scans can be a powerful tool for conveying emotion and meaning, allowing viewers to understand the significance of a building even if they have never seen it in person.

Shortly after the Reunion House was listed as the City of Los Angeles Historic-Cultural Monument, a group of University of Southern California Master of Heritage Conservation students studied the house and produced an assessment and recommendation report for Reunion House (National Park Service, 2022a). The report was organized with each feature with a caption number, photograph(s), caption, estimated date, feature type, significance, description, condition class, condition description, and recommendation for treatment. Photographs, description, and condition description mainly surround the geometrical shape, material, and physical condition of features. A photograph next to the written description of an architectural feature can provide direct information about the feature itself, such as its size, shape, color, and materials. However, it is limited in its ability to relate individual features to the larger entity of the house. For instance, a photograph of a window may not provide enough information to determine how the window relates to the overall design of the house, such as its position within the overall floor plan, or how it contributes to the overall aesthetics.

A technical plan needs to be established to bridge the gap between text and perception, segment and totality. To do this, the following features and elements should be taken into account for each task related to Heritage Conservation:

Table 2-2: Scanning focus of each heritage conservation tasks

Site Survey	***Documentation***	***Monitoring***	***Education***
Interior Wall	projecting beams extending beyond the building envelope, either floating free, or terminating in a post as a “spider leg”	Exposed post and beam structure	Interior decoration, staging
Exterior Wall	Deep overhangs, often with strip lighting flush with overhang and at its edge. rounded post caps, created by adding a separate piece of lumber, flat on one side and subtly rounded on the other, which fit over a squared 4’ – 4”, thus softening the visual effect of an otherwise rectilinear composition	Wall	Exterior, landscape, public road
Door, window, and opening location	A rhythmic distribution of details, wall treatments, textures, and windows	Ceiling	
Lot terrain		Floor	

2.5 Summary

This chapter described 2.1 3D scanning’s application in general fields of industry, 2.2 3D scanning’s application in the field of Heritage Conservation, categorized with different working principles, 2.3 past studies using a smartphone for scanning, 2.4 past research and documentation done for the Reunion House, and 2.5 summary.

Strength and limitations of various professional scanners are thoroughly studied. They are more than capable of documenting and providing useful information for future design and conservation work. Different types of scanners exhibited their distinctive vantage points and shows their limits. Studies and technologies work on offset these limitations and result in higher quality of scanned data.

Triangulation, pulse, and phase-comparison scanners are the most commonly used technologies in the field of heritage conservation. These scanners produce digital data which serves as the basis of any preservation project. With the rise of more affordable and portable methods such as smartphones equipped with LiDAR sensors, more researchers are investigating the accuracy of these scanners. While much work has been done in this area, further studies need to be conducted to determine which method is best suited for which type of heritage conservation project. This would help both professionals and amateurs acquire the necessary data for their projects.

The Reunion House at Silver Lake was selected as a case study. Listed as City of LA Historic-Cultural Monument in 2021, Barbara Lamprecht and Neutra Institute developed a comprehensive document including survey, historic context statement and architecture description. In the same year a group of students, from USC heritage conservation program conducted an assessment and recommendation for the property. The package of documents offers a wealth of information, both tangible and intangible, that can be used as a basis for further research on the use of smartphone-scanned data. In addition, there is potential to incorporate newer, more cost-effective technologies such as scanning to enhance the document package, which could be applied to areas such as site surveys, monitoring, and education in the field of heritage conservation (Figure 2-14).

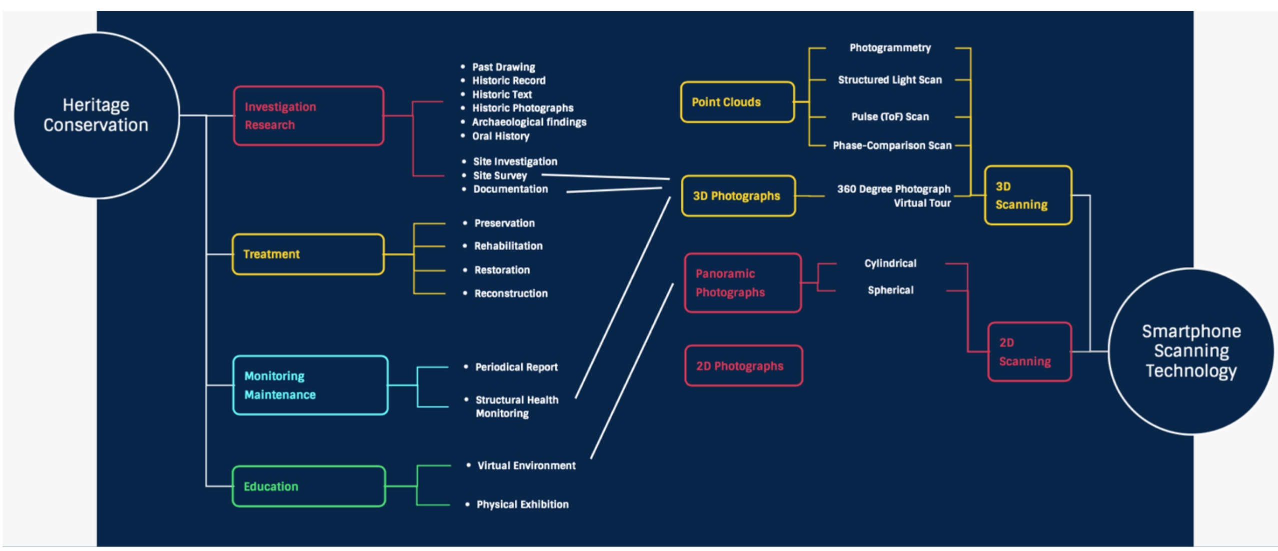


Figure 2-14: Smartphone scanning technologies match with heritage conservation goals

Chapter 3 Methodology

Chapter 3 will discuss the scanning device and software using for scanning; site survey for heritage conservation using smartphone, including software selection, data acquisition, data processing, comparison to traditional methods, and case study done by professional scanners; documentation for heritage conservation; monitoring for heritage conservation; and education. Chapter 4 will discuss all the steps in more detail using the test scans as examples.

Scanning has been used in various aspects in the field of heritage conservation. The high expense and sophisticated operation of a professional scan can sometimes be infeasible with respect to cost and inaccessibility of sites. An alternative scanning method is proposed using a portable smartphone equipped with a high-resolution camera and LiDAR sensors. Smartphones can capture 2D photographs, cylindrical panoramic photos, 3D Matterport pictures, photogrammetry, and some of them can even generate LiDAR point clouds. Two case studies are proposed: a partial study of the Hoose Library of Philosophy at USC and specific areas at Richard Neutra's Reunion House in Los Angeles, CA. HC tasks, namely site survey, documentation, monitoring, and education, will be practiced with the proposed method. The methodology will emphasize distinctive purposes for each task. An iPhone 13 Pro will be used to examine the performance with selected iOS apps. Additional free software will also be applied in processing data. The results of the test scans at Hoose Library and the case studies at Richard Neutra's Reunion House will be compared respectively with traditional methods and high-end scanners.

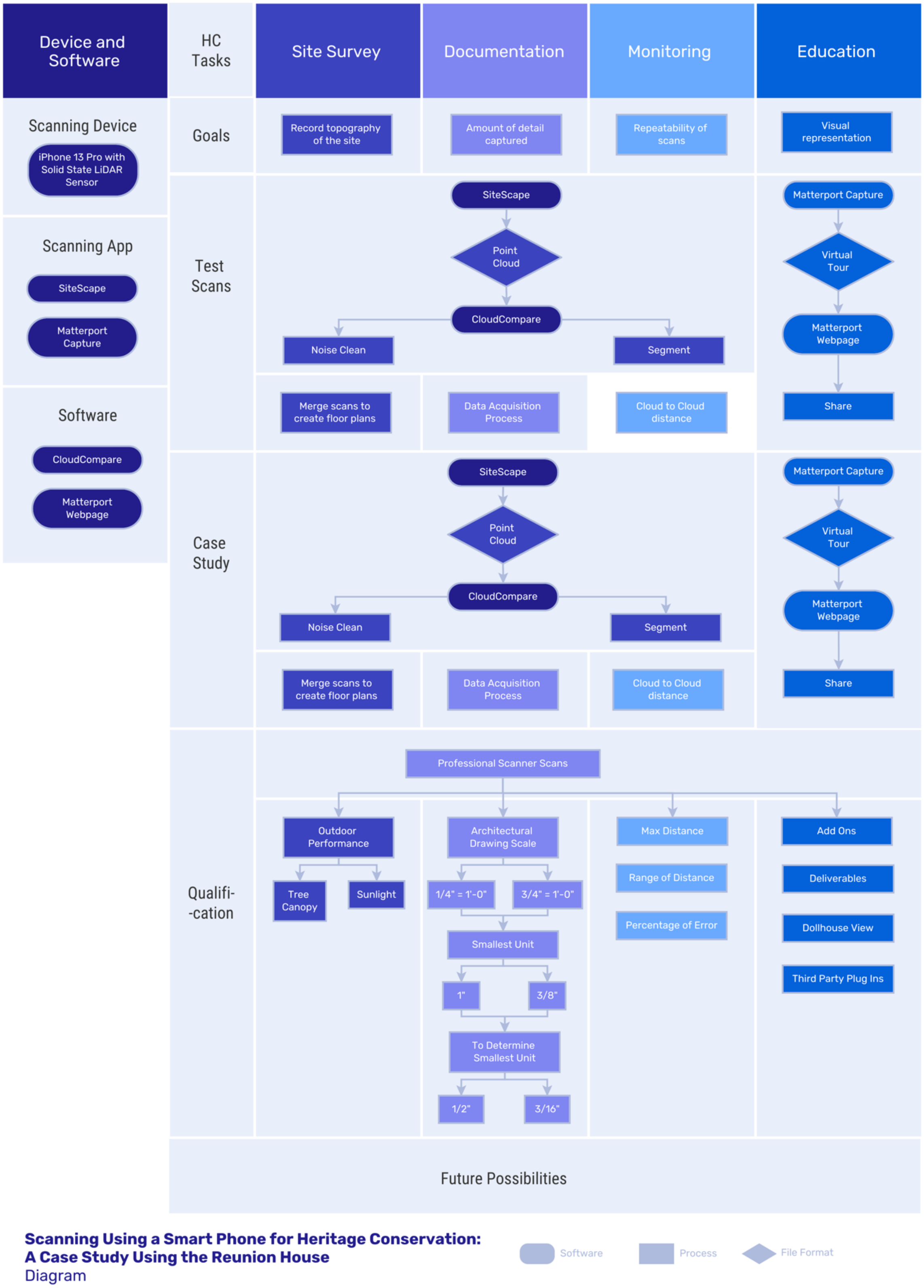


Figure 3-1 Proposed methodology

3.1 iPhone 13 Pro as scanning device

The LiDAR system was first installed on Apple products in 2020 with the release of iPhone 12 Pro and iPad Pro (4th generation). In the very next year, Apple released their iPhone 13 Pro and iPad Pro (5th generation), which are also equipped with LiDAR systems. Even though released in different series, the LiDAR technology and equipment used in all Apple products are the same (Stein, 2022). The differences among these smart devices lie in the size of screen, storage memory, and processing chips.

The proposed method will be executed with an Apple iPhone 13 Pro, released in September 2021, priced. It has three Pro 12MP rear cameras, telephoto, wide, and ultra-wide cameras - and a LiDAR sensor, with a total weight of 203 grams (7.16 ounces). With its height of 146.7 mm (5.78 inches), a width of 71.5 mm (2.82 inches), and a depth of 7.65 mm (0.30 inch), iPhone 13 pro is portable and lightweight. With cost-effectiveness being the concern, the price of the iPhone 13 Pro is US dollar 999.99 plus tax (as of October 2022).

The LiDAR sensor embedded in Apple products is claimed to be using ToF technology, which is considered solid-state LiDAR (SSL) as they do not have to move parts for a scan (Murtiyoso et al., 2021). The LiDAR scanner is responsible for measuring the distance from the device to objects in its vicinity, while the projector sends out infrared light. The image sensor captures the light that is reflected off of the objects around the device, and the processor then uses this information to create a point cloud file of the surrounding environment.

Figure 3-2 Using smartphone scan a cultural heritage (Crabbe, 2013)

3.1.1 Scanning app: SiteScape and Matterport

SiteScape is a software program that uses LiDAR scans for architecture, engineering, and Cconstruction industries. It has a user-friendly interface; after signing up for free with name, email, and password, a camera page would show directly (Figure 3-3). There are three buttons at the bottom of the interface; from left to right are customizable acquisition settings, tap to start, and album. The app allows customization of “Point Density” (“low”, “medium”, or “high”), and “Point Size” (“low”, “medium”, or “high”) (Figure 3-4). The “point density” option can change the number of points captured; the option of “medium or high” can capture two or four times the number acquired in “low” quality mode, which impacts processing time and produced data (need a citation here). The “point size” option only affects the dimension of dots visible on the interface, which does not impact the obtaining of data.

Figure 3-3: SiteScape iOS app

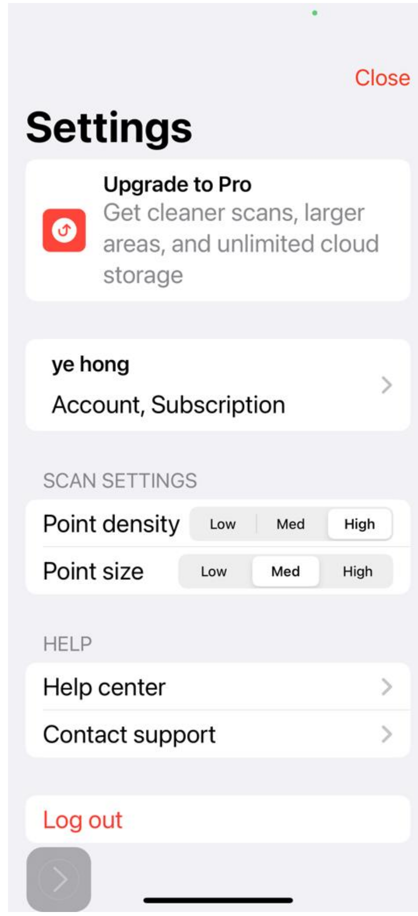


Figure 3-4: SiteScape parameter

The iOS application SiteScape version 1.6.5 by SiteScape Inc. is then chosen as it meets specific needs related to cultural heritage documentation: 1) the app can is free to download and use (upgrade option is available for more functions) 2) acquisition settings can be easily adjusted upon requirements 3) 3D models can be generated as a point cloud. These attributes allow an average person without professional experience to operate the scan with no cost and generate the final product with various raw data sets.

The Matterport company released Matterport Capture app in 2020 to bring 3D data acquisition to the iPhone. In both scans at the HLP and Reunion House, version 5.2 of Matterport Capture app will be used. The application comes with free user licenses and the accounts that are accessible for scanning practice. Its easy-to-use interface allows people in the field of historic preservation to use it as a tool assisting their projects. Matterport Capture has multiple scan options including scan types of “3D Scan” and “360 Capture” with scan modes of “LiDAR Scan”, “LiDAR Complete Scan”, “Simple Scan”, and “Complete Scan” (Figure 3-5). According to Matterport. Inc, “the 360 Capture will generate a 360° view of a space. A 3D Scan will generate the data needed to create a 3D model or virtual tour of a space.

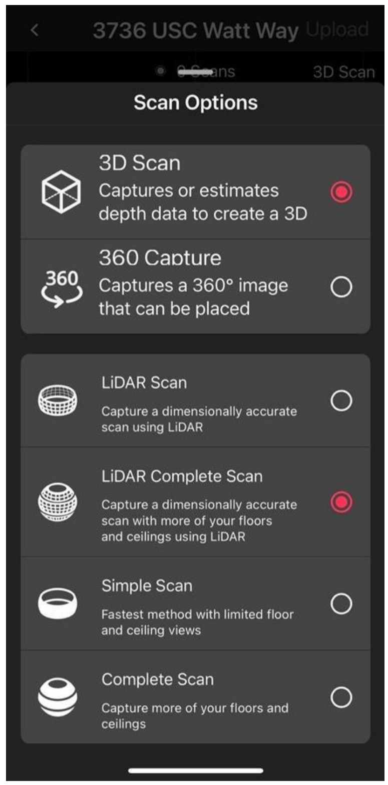


Figure 3-5: Matterport Capture iOS app (Matterport, 2022)

3.2 HP survey with smartphone

A survey allows for a systematical identification and record of heritage resources in the community. Site surveys are labor intense work that it requires researchers go out to the field and record buildings and terrains on site. The information documented by researchers on site will be significant in creating a foundation for the joint of physical condition of the site and archival knowledge. A site survey will be created through smartphone scanned data and compared with traditional map and floorplan techniques, as well as a site survey conducted with high-end scanners.

3.2.1 Software selection – SiteScape

SiteScape is selected as the smartphone phone app used for generating heritage conservation site surveys, because the application allows for pause during a scan. Different density of scans gives more options to researchers. A high density scan might be used if you needed to capture a lot of detail in a short amount of time. For example, when creating a map of a small area, a high-density scan could capture the space with more points describing it. A low-density scan might be used if you needed to capture a large area but did not need a lot of detail. For example, if you were creating a map of an entire building, a low-density scan would be a better choice as it would capture the area in thin layer of points and allows for larger scanned area.

3.2.2 Data acquisition process

In the data acquisition process, SiteScape encourages a distance between 3-12 feet (1-4 meters) from the scanned objects. To capture quality data, the scan is needed to be executed in a smooth path, avoiding fast and large movement, especially in horizontal direction. SiteScape noted that to scan the outdoor environment, direct sunlight should be avoided, cloudy days, post dawn or before dusk are more suitable conditions. Test scans will be implemented at the Hoose Library of Philosophy before the case study scan at Reunion House being conducted. For the convenience of the tenant of Reunion House and the researcher, scans will be arranged in afternoons. Scans of interior space will be performed prior to the garden, with a north to south order depending on the location and lighting condition of the selected rooms/ features. Each scanning object will be scanned at least three times with parameters of point density with “Low”, “Medium”, and “High”. Repeat scans are encouraged when initial trials have visible holes, double layered points, or missing areas.

During each scan, a timer will be set in recording the human effort in completing a scan by smartphone. Monitoring the device's condition will also be noted. SiteScape mentioned an overheated central processing unit can drastically reduce scan performance, and low battery would also impact scan quality. When the temperature of a smartphone screen or back panel is higher than an average human hand temperature, the scan procedure shall be paused until the temperature drops back to normal. Phone battery shall remain over 50% over the whole course of scan, data processing, and synchronizing. A portable power bank or phone charger should be available at the scan site.

Misleading registration of geometrical data will occur when there is only one surface or texture (wall, carpet, or grass) within the scanning frame for several seconds. This is because SiteScape automatically registers the LiDAR sensor that the situation will cause miss-aligned points. To prevent the misleading circumstance, scans are encouraged to keep multiple features on screen. A timer will record how long each scan takes.

After scans complete, each point cloud will be synchronized into SiteScape cloud, initially processed, and downloaded in three different formats (.ply, .rcs, .E57) respectively (free user license only allows one model at a time). A hands-on and free cost software, CloudCompare, will be downloaded and used for data processing.

The process remains the same for test scans and the case study.

3.2.3 CloudCompare: merging multiple scans

The free desktop software CloudCompare will be used for data processing after the point cloud data is downloaded locally (Figure 3-6). Raw data contains noises and unwanted parts, thus before any analysis started, scan data need to be cleaned and copped. Automatic noise cleaning can be achieved using SOR and Scalar fields function in CloudCompare, and cropping can be done with the scissor icon on the toolbar.

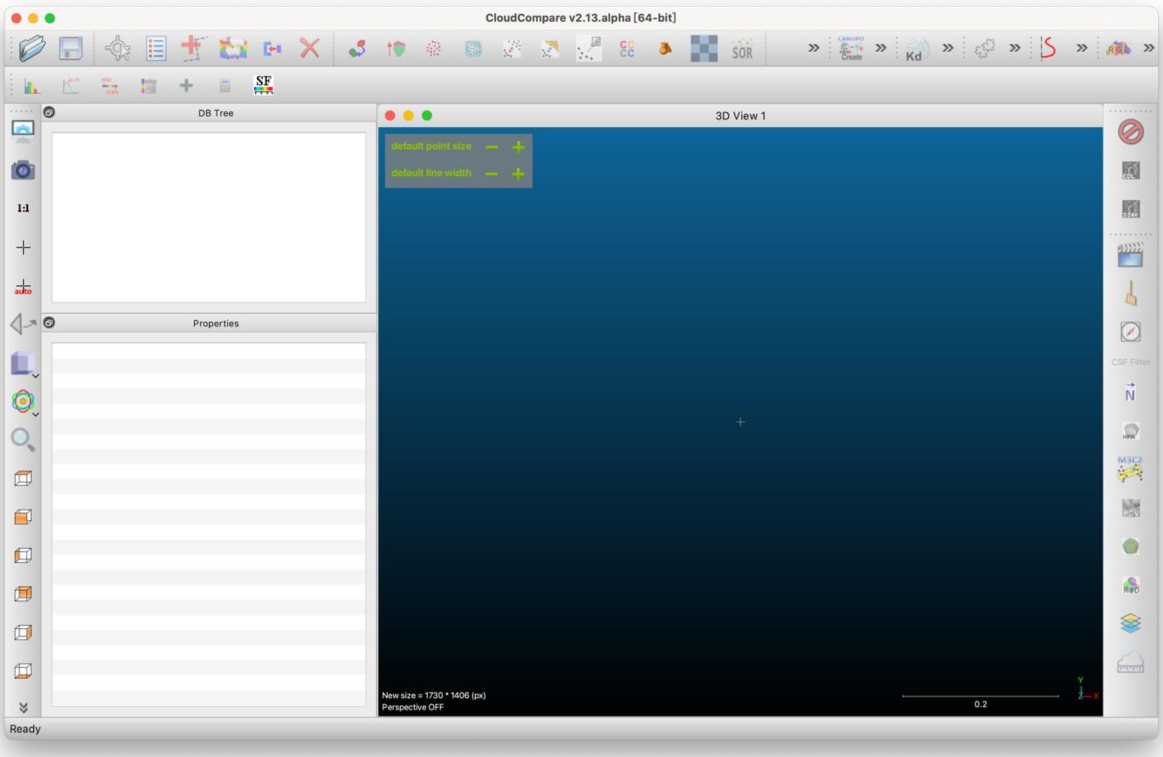


Figure 3-6: CloudCompare interface

In order to achieving a survey, the methodology needs to use multiple point clouds in generating a large floorplan or map. Smartphone scanned point cloud has a maximum file size, which means the app is not capable of scanning the entire building or site with one scan. The method of scanning a space with multiple scans, and merge them together in CloudCompare will be used. Each scan will slightly overlap the previous scan with the assist of reference points.

3.2.4 Smartphone acquisition qualification

Smartphone acquisition result for survey will be evaluated based on its feasibility, quality of result, and limitations and strengths of the methodology. The analysis will involve considering factors such as the cost and time required for data collection, as well as the availability of suitable equipment and personnel. The quality of the data collected will also be accessed, including factors such as the clarity of the images, the accuracy of the measurements, and the consistency of the data. Meanwhile, recommendation will be made based on research result to assist heritage conservation site survey purposes.

3.3 HC documentation with smartphone

Historic preservation documentation aligns with the purpose it serves. Most generally, documentation requires capability of recording geometric shapes, color, texture, and interrelationships between architectural features. The iOS application will be selected and installed, parameter settings and interface will be studied. Acquisition procedure will be performed with the device with different parameters. Two comparisons will be made: the expense, operation, and results will be compared with 1) traditional methods of historic preservation documentation, 2) high-end scanners application in the field.

3.3.1 Software selection – SiteScape

When documenting heritages, architecture historians, cultural resource managements, and heritage conservationists are concerned with the amount of detail being recorded. The geometry of character defining features and architectural features shall be accuracy described in documentation. The smartphone software selected for documentation purpose should be capable of registering concreteness of a detail of architectural features, including texture, shape, and color.

Beyond the competences of the application, cost and operability by non-technicians as factors should also be considered when selecting smartphone applications. iOS scanning app SiteScape is then selected. As introduced in 3.1.2, SiteScape is free for use, easy operation, and produce point clouds with different parameters, which meet the needs for heritage conservation documentation.

3.3.2 Data acquisition process

The same procedure as 3.2.2 Data Acquisition Process will be practiced for documentation purposes, focusing on architectural features and character defining features mentioned in Chapter 2, Table 2-1. The process remains the same for test scans and the case study.

Table 3-1: Scanning focus for case study at Reunion House

Features to Scan	***Past Documentation***
Interior, exterior wall, ceiling, floor	original drawing
Projecting beams extending beyond the building envelope, either floating free, or terminating in a post as a "spider leg"	photographs
Windows, doors, and their location (a door connecting kitchen to study was changed to a bookshelf. The time of alteration was determined the same time as the kitchen alteration, which post the period of significance)	original drawing, photographs
Current Kitchen (Dion and Richard did multiple alterations to the kitchen, including the cantilevered countertops in the kitchen/breakfast nook, large mirror on the north side of the kitchen wall, and a second mirror in the southwest corner of the kitchen.)	original drawing, photographs
Interior decoration, staging, exterior, plant canopy	photographs
Built in furniture	photographs, drawings

3.3.3 Using CloudCompare processing data: increasing precision

The same automatic noise cleaning and cropping procedure as 3.2.3 will be conducted on the data acquired from 3.3.2. Then, the goal of increasing precision will be introduced.

Precision describes how close measurements of the same item are to each other. In an accurate but not precision situation, points will surround the geometry of object, but scattered around. To increase precision, two scans will be registered together in testing if overlay will increase the number of points describing the same space. The number of total points describing the defined space will then be used for evaluating the methodology’s competence in increasing precision.

Two overlay and processing orders of the two scan data will be considered

1. Noise clean of each scan will be accomplished before the two scans being overlaid
2. Noise clean will be accomplished before the two scans being overlaid.

3.3.4 Smartphone acquisition method qualification

The point cloud data acquired with smartphone devices are evaluated on its ability to record geometric shapes, surface textures, color, complex structures, interrelationships between different architectural features according to American Historic Building Survey suggestions. Beyond its performance, level of operability will also be compared with traditional methods of measured drawing, large format photographs, and written descriptions. Whether an average person in the field of HP can or cannot operate this method is going to be discussed. Time needed for a quality scan, potential difficulties, and basic data processing procedures will also be discussed. Aiming at mitigating the cost-effective concern for HP projects, the cost of a full scan will be included in the comparison as well.

3.4 Monitoring

How cultural heritages change overtime can be watched through monitoring its physical condition. The condition can be recorded with 3D scanning technology. Heritage conservationists can observe the change through comparing current scan with scans taken years ago. If a building structurally shifted, the two scans will have distance instead of accurately overlaying each other. Thus, each scan needs to closely measure the true or accepted value in order for researchers distinguish the nuance in structural changes. The smartphone and desktop software selected for building and site monitoring will be explored. Acquisition and data processing will be practiced in test scans before scanning the case study at Reunion House. Comparisons will be made on the expense, operation, and scanning data result with 1) traditional methods of historic preservation documentation, 2) high-end scanners application in the field.

3.4.1 Software selection – SiteScape

To monitor a building, the change of the building's condition and geometry over time need to be documented and contradistinguished. This could involve monitoring the construction of a new building, the demolition of an existing one, the erosion or accumulation of land, or any changes to the existing terrain of the building or site. The monitoring would include measuring the changes in height, width, length, angle, and any other geometric characteristics of the building or terrain. This would be done through the use of surveying equipment, such as total stations or drones. The data collected would then be used to create detailed documentation of the changes and be used to inform future decisions about the building or site. The collation between documentation taken from different times can spot changes in material and structure.

This includes cracks, deterioration, and shifts in structure. Cracks and deteriorations can be sighted with human eyes, but the nuance shifts in a structure are hard to observe. The iOS app chosen for monitoring purposes should be able to export point clouds for further data processing. The free iOS app SiteScape introduced in 3.1.2 is then chosen because it meets the needs to monitor a building.

3.4.2 Acquisition for HP monitoring

The same procedure as 3.2.2 Data Acquisition Process will be practiced for monitoring purposes. The data obtained from this process will be used in CloudCompare for analysis. Before scanning, make sure the environment is prepared for a successful 3D scan. This includes clearing the area of any potential obstructions, ensuring adequate lighting, and setting up the smartphone app. The focus of monitoring acquisition should focus on the structural wall, ceiling, columns, and beams (if visible).

The process remains the same for test scans and the case study.

3.4.3 Using CloudCompare processing data: increasing accuracy

Two scans of the same space of test scans (Scan 1 and Scan 2) will be used in data processing. Both scans need to be cleaned and cropped follow instructions in 3.3.3. The accuracy of the point cloud data can be improved with the techniques such as outlier removal and noise reduction.

The methodology of overlapping two scanned point cloud data is then developed to further increase accuracy. Accuracy describes how close a measurement is to the true or accepted value. Thus, the distance between the two clouds exhibits their ability to accurately describe the target. This process involves combining two separate point clouds that have been captured from different trails to create a more accurate and complete 3D representation of a space. The process begins by aligning the two point clouds to each other. After the two point clouds are aligned, the next step is to calculate the differences between the two clouds. This difference is then used to determine the accuracy of the combined point cloud with cloud-to-cloud distance function in CloudCompare.

3.4.4 Smartphone acquisition qualification

Smartphone acquisition for heritage conservation monitoring purpose will be evaluated based on the repeatability of smartphone scans. Through cloud to cloud distance computation, the differences will be visualized and compared to professional scanner's accuracy. Recommendations will be made based on research results.

3.5 Education

Heritage conservation is the process of preserving and protecting the natural and cultural heritage of a place. It involves the identification, protection, conservation, and management of places, objects, and other cultural resources that are of special importance to a particular community. Heritage conservation in education refers to the teaching of methods and practices of heritage conservation in school settings. This includes lessons on history and culture, the importance of preserving and protecting the heritage of a place, and the role of students in preserving and protecting their own cultural heritage.

Visualizing heritage conservation in education can involve a variety of different approaches, such as creating a visual timeline that maps out the history of conservation efforts, creating infographics that illustrate the environmental, economic, and social benefits of conservation efforts, creating interactive maps of protected areas and monuments, and creating spatial experiences to bring heritage conservation to life, where 3D scanned data can be helpful. The ability to visualize and provide information becomes the main concern for this purpose. A smartphone app will be selected in obtaining spatial data and create the experience in a cost-effective method. Its competence in delivering spatial experience and shareable content will be compared with traditional teaching approaches and projects done with professional scanners and crews.

3.5.1 Software selection – Matterport

The Matterport iOS app is selected for the purpose of heritage conservation education. As mentioned in 3.1.2, A virtual tour in the visualization of space is a computer-generated simulation of physical space. The app is capable of obtaining spatial images and experiences with 360-degree photographs and the virtual tour function. Matterport software become a competitive candidate for also because of its powerful and accessible data processing engine. The product of the scan can be exported to a webpage and links, which can be viewed by a mass audience on the internet world-widely.

3.5.2 Data acquisition process

For a one-floor interior space, the tripod can be set to the height of human eyes. After setting up the smartphone device on the tripod, one can start the scan by clicking the capture button. Matterport Capture will provide instructions to point the phone camera at a series of white dots (Figure 3-7). During one capture, the process can be tracked by looking at the pink rings around each of the dots. After 360-degree rotation is completed, the tripod and device shall be moved to the abutting scanning spot, which according to Matterport Help Center, is around 5-8 feet (1.5-2 meters) from the previous scan. The same scanning process should be practiced at each scan spot. At least three scans should be done to complete one survey. 360 Capture relies on AI technology in calculating depth, which is not interfering with strong light, while LiDAR scan will be affected by such lighting conditions. Thus, during a scan with LiDAR mode, strong light should be avoided.

Figure 3-7: Matterport Capture interface on iPhone

3.5.3 Using Matterport webpage processing scanned data

The obtained data will be synchronized to Matterport Cloud, where data can be viewed and processed online through a desktop (Figure 3-8). Matterport webpage allows user to upload and edit their capture of space. With a free user license, the cloud only allows one scan to be processed at a time. A link can be created for public viewing of the 360 degree photograph virtual tour. Each scan should be saved as a shareable link, then the next scan can be synchronized and processed. After all scans been processed, a comparison among each trial with the link should be conducted, a best performance will then be selected. The virtual tour can also be implemented into websites and shared.

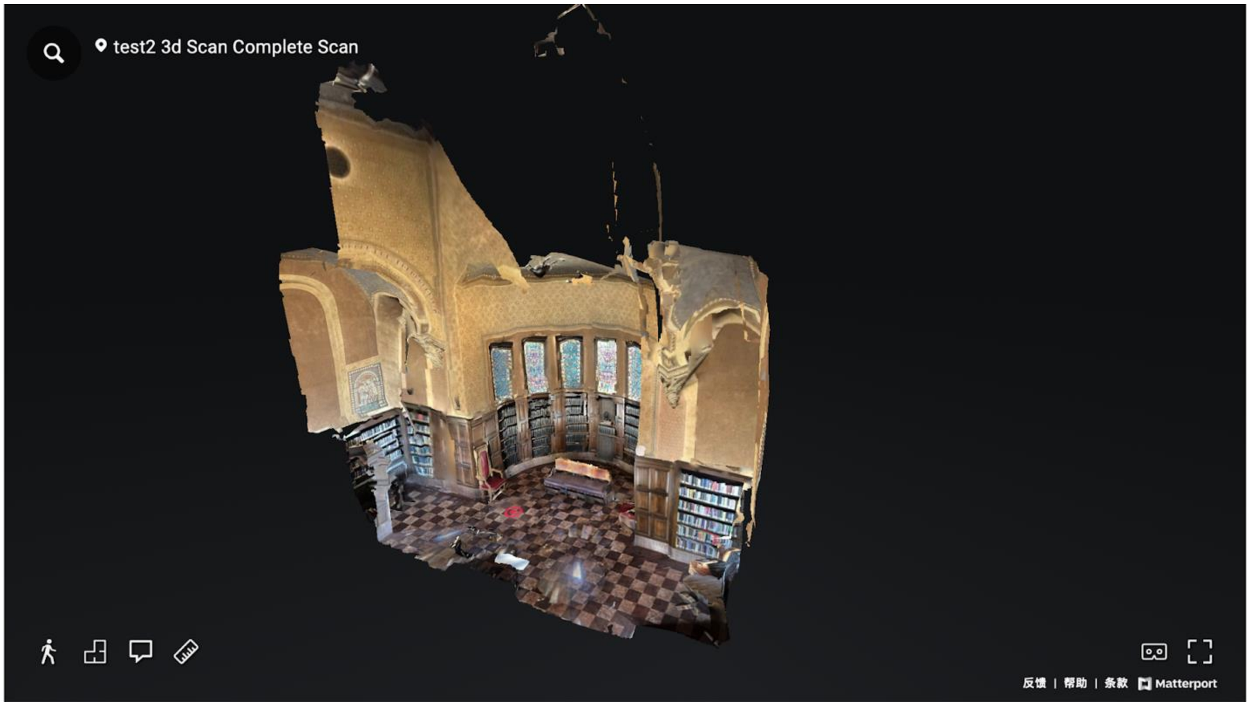


Figure 3-8: Matterport webpage editing interface

3.5.4 Smartphone acquisition qualification

Smartphone captured virtual tour will be compared to virtual tours available online. Deliverables and downloadable files will be exported to Matterport project webpage and manipulated; test including dollhouse view, measurements, and virtual tours.

3.6 Summary

Chapter 3 discussed the scanning device and software using for scanning; site survey for heritage conservation using smartphone, including software selection, data acquisition, data processing, comparison to traditional methods, and case study done by professional scanners; documentation for heritage conservation; monitoring for heritage conservation; and education.

Following this methodology, one can use a smartphone and select software to scan a heritage site in reaching HC goals of surveying, documenting, monitoring, and educating. Matterport and SiteScape smartphone apps were chosen for their outstanding capability in meeting these research goals. SiteScape was designed to use in data acquisition process of intentions including surveying, documenting, and monitoring. Computer desktop software CloudCompare would be used for registering multiple scans, increasing accuracy and precision. Smartphone scanned data would then be compared with traditional methods and a professional scanner scanned data. Matterport was selected for the goal of education, the data acquisition, processing, and visualization would be juxtaposed to traditional method and a high-end scan.

Chapter 4 will describe in further detail the methodology described using the test scans as an example. Chapter 5 will be conducted at the Reunion House as a case study.

Chapter 4 Test Scans Using the Smartphone

Chapter 4 describes test scans for different heritage conservation intentions at the Hoose Library of Philosophy at the University of Southern California. In Chapter 4, a step-by-step detailed instructions for using the app and software operation are provided. In addition, preliminary results of test scans are given at the end of the chapter. The comparison to traditional methods and professionally scanned data will be carried out in Chapter 5 as a case study.

Chapter 4 is a start-up guide for scanning acquisition and data process. Scanning and processing for the four heritage conservation purposes will be taught step by step in 4.1 Smartphone scan for heritage conservation documentation, 4.2 smartphone scan for heritage conservation survey, 4.3 smartphone scan for heritage conservation monitoring, 4.4 smartphone scan for heritage conservation education (Figure 4-1).

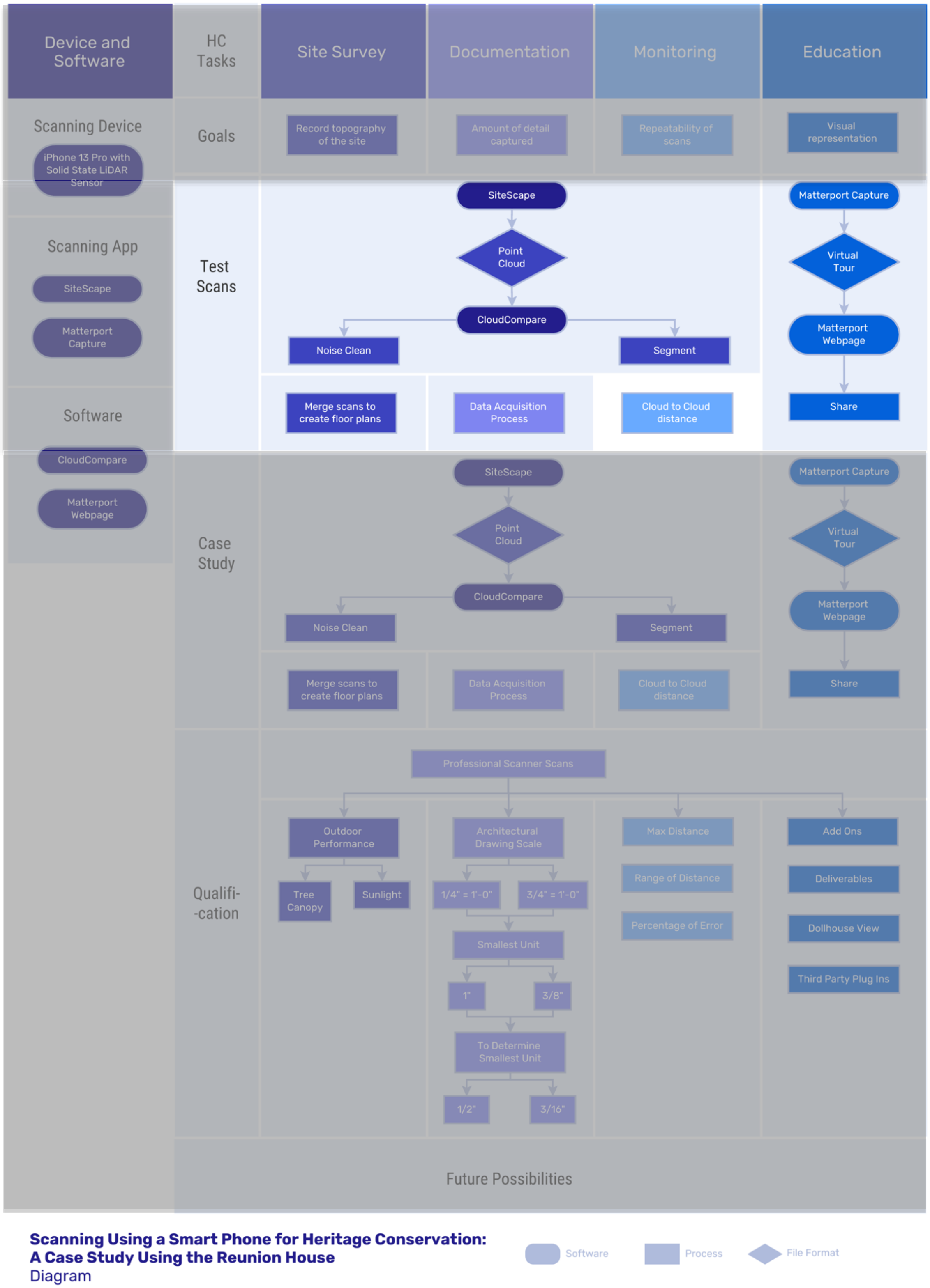
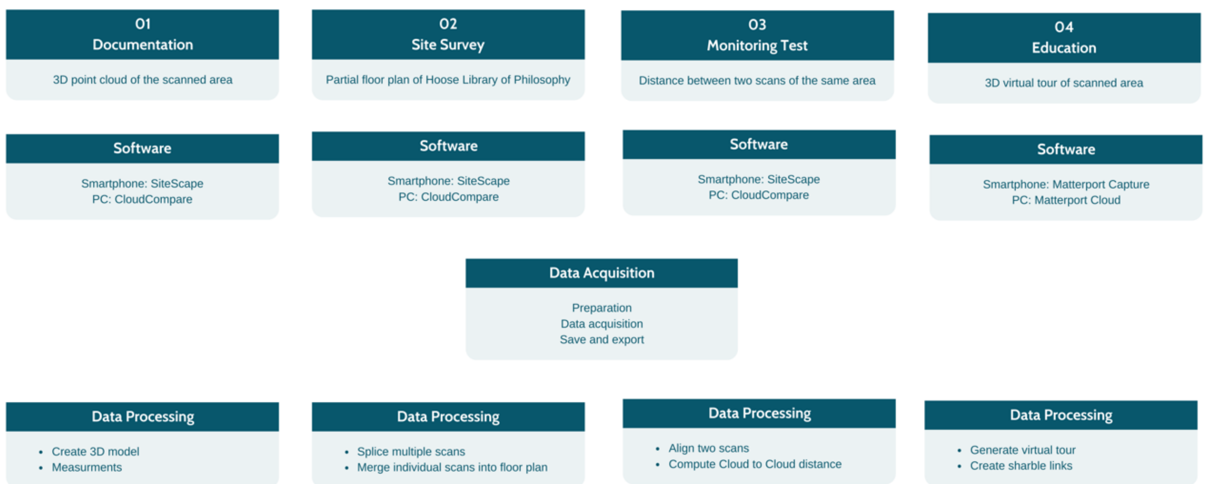


Figure 4-1: Chapter 4 content diagram

In each of these sectors, test scans will be conducted with different approaches and software in achieving distinct goals (Table 4-1).

Table 4-1: Test scan tasks of Hoose Library for heritage conservation purposes.



Prior to scanning, the smartphone should be fully charged and the software SiteScape and Matterport Capture installed. The desktop processing software CloudCompare should be also downloaded. A tripod is recommended, if not, a long stick or post can also assist the work. Other than the uploading and downloading process, internet connectivity is not required for data acquiring procedures.

SiteScape and Matterport Capture(phone app) can be downloaded from Apple Store.

SiteScape project page can be accessed from https://app.sitescape.ai/projects

Matterport Cloud can be accessed from https://my.matterport.com

CloudCompare (desktop computer) can be downloaded at https://www.cloudcompare.org

4.1 Smartphone scanning overview and directions for documentation

For the purpose of documentation of cultural heritages, scanning with smartphone will be conducted with steps introduced in the following "getting start guide." The goal of this section is to validate the precision of different scanning modes.

Each of the multiple scans for an HC documentation of an environment followed these steps. To scan an enclosed space, the researcher should start facing one corner of the space, with a distance of 3-12 feet to the scanned object. After setting up the proper parameter, the researcher should hold the smartphone device vertically with both hands in a position where arms next to the body tightly, and ensure the screen is clearly in sight. After pressing the start button, the researcher should use the scanned object as a center, slowly move left and right on foot. After one feature is captured from left, right, up, and down, the researcher should gently move to the abutting features and scan. In the case of the test scan, the researcher should face the target surface, start scanning from right to left (southwest to northeast). The person can move arms up to down, right to left in capturing more detail of the bookshelves (the example used in 4.1.1). When the first shelf is scanned, research should step left with device sensor facing the shelf and always ensure there is no gap or hole in scanned data.

As the scan starts, the camera view will be disabled; when moving around the scanned object, captured points will gradually show up on black screen so holes from data can be visible. Overlap layers of data can be misleading and inaccurate; to prevent the situation, researcher should avoid scanning the same area twice. During the scanning process, researcher need to scan continuous surfaces, with rich features in sensor sight. For the purpose of generating maps and locations of walls and features, plane surfaces should be avoided. As much as possible features and details should be included. The point count bar at the bottom of the screen shows the total points captured; scanning will stop when the bar is full. A single scan has limited allowed point, more scans might be needed for the entire space; the researcher should take as much scans as possible to fully document the space. Each scan should overlap the previous scan for data register. After a scan is accomplished, SiteScape allows scans to be synchronized into the clouds, where users can view it on a desktop with a web page. With a free user license, one can synchronize one point cloud at a time.

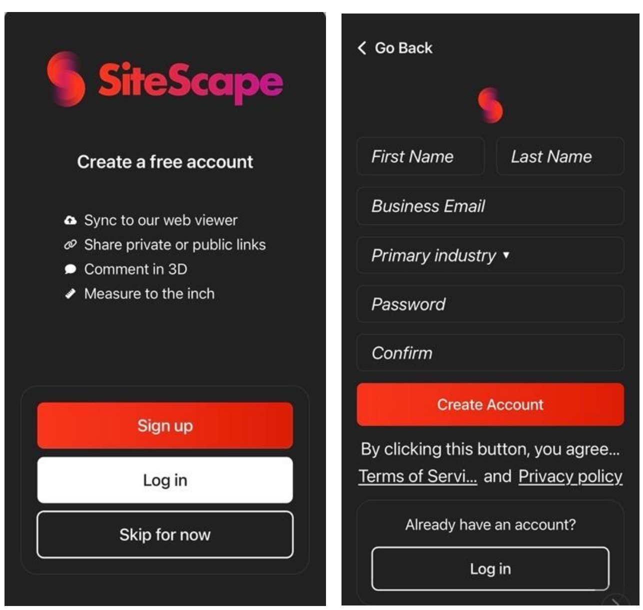
4.1.1 Data acquisition

Data acquisition of smartphone scanned heritage conservation documentation including major steps of software preparation, data acquisition and exports. The smartphone application in use is SiteScape.

I. Preparation

a) Havethe smartphone application SiteScape downloaded to the device, and the software CloudCompare installed to a desktop computer.

b) Open SiteScape, sign up a free account (Figures 4-2 and 4-3).



Figures 4-2 and 4-3: SiteScape register interface

c) Remove unwanted furniture or objects from the space to be scanned. The examples shown are from the Hoose Library of Philosophy (Figure 4-4).

Figure 4-4: Hoose Library of Philosophy

d) Click on setting button, change point density to Med and Point size Low, then click Close (Figures 4-5, 4-6, and 4-7).

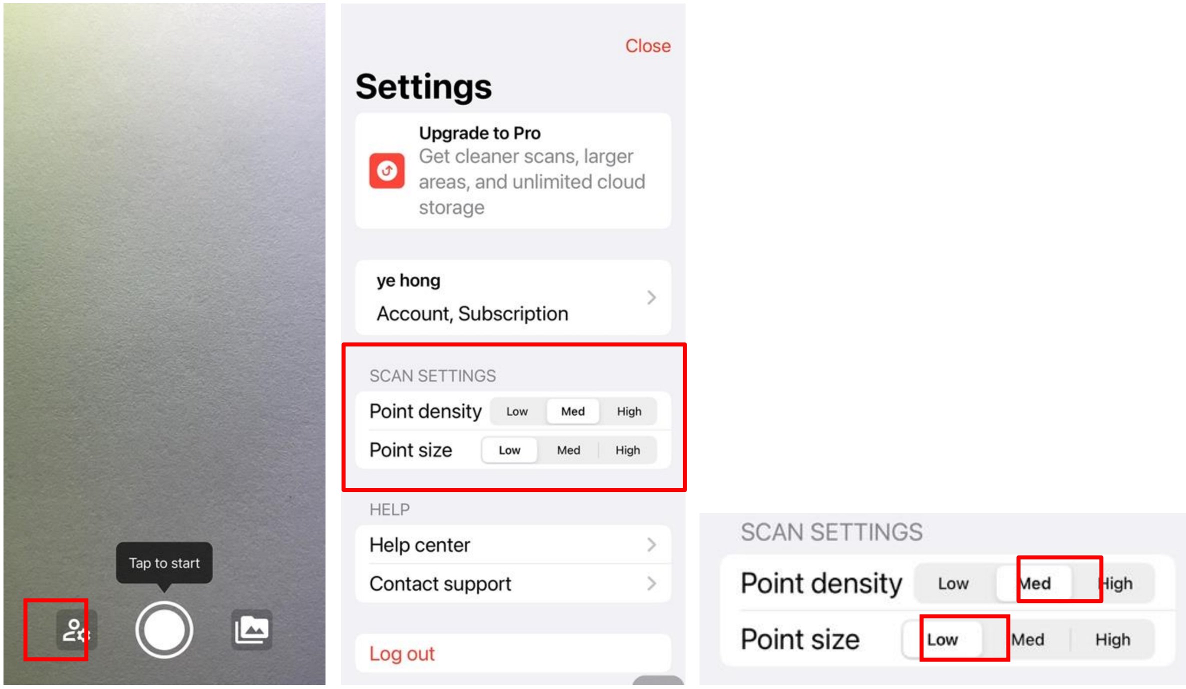


Figure 4-5, 4-6, and 4-7: SiteScape setting button and scan setting

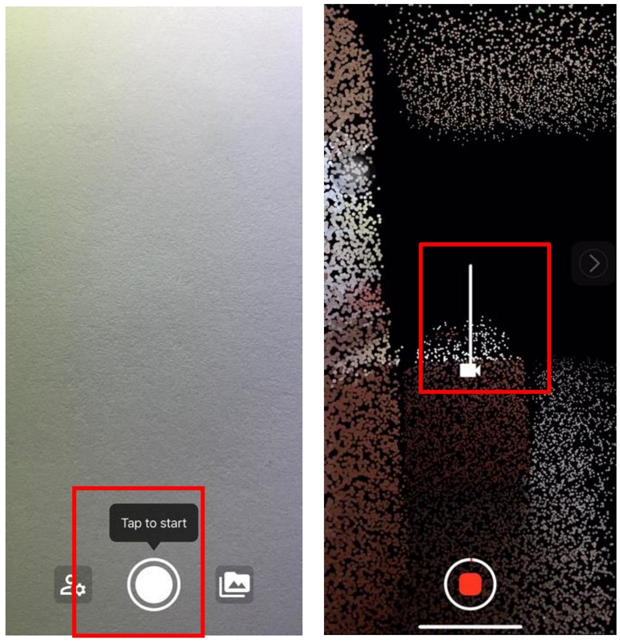
II. Data Acquisition

Smartphone scanned data can be acquired with or without the assist with a tripod. The two methods are introduced here.

Method A: Without Tripod (If equipped with a tripod, see method B)

a) Hold smartphone device vertically with both hands, arms next to the body tightly. Stand 5 feet away from the scanning object to ensure that the smartphone camera can capture rich and detail features

b) Tap the circle button to start scanning. Once started, the camera view will be turned off (Figures 4-9 and 4-10).



Figures 4-9 and 4-10: SiteScape operation interface and camera view adjust

c) Set the scanned object in the center; slowly move left and right on foot. Capture the object from left, right, up, and down with colored points on screen fully describe it.

d) Gently move to abutting features and scan repeating step 6, avoiding features from reappearing on screen.

e) During scan, pay attention to process circle at the bottom of the screen, when process bar is full, a scan is automatically completed (Figure 4-11). A scan can be paused and resumed by clicking the circle. If the scanning is not going well, one can restart (Figure 4-12).

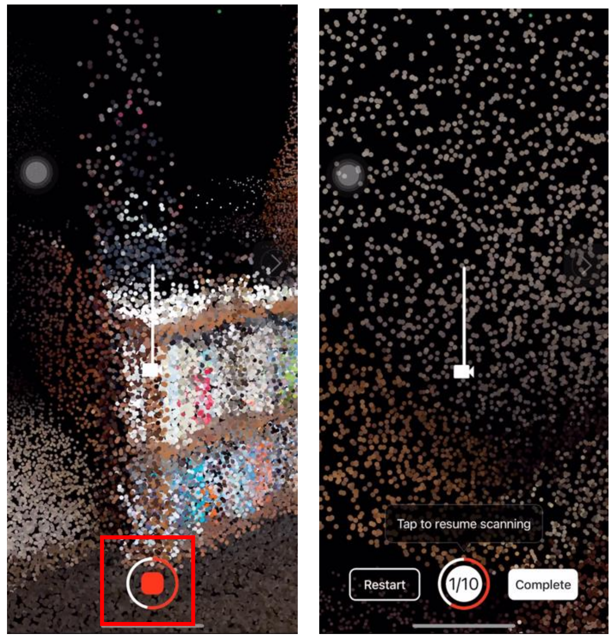


Figure 4-11 and 4-12: SiteScape pause and resume scanning button

f) The scan will automatically complete when the process circle full. To complete a scan when the circle is not full, click pause, then the complete button. Acquired data will be shown in a virtual space from screen; the user can choose to Close, Export, or Sync to Cloud (Figure 4-13, 4-14). Click on Continue & Replace if using free account (Figure 4-15).

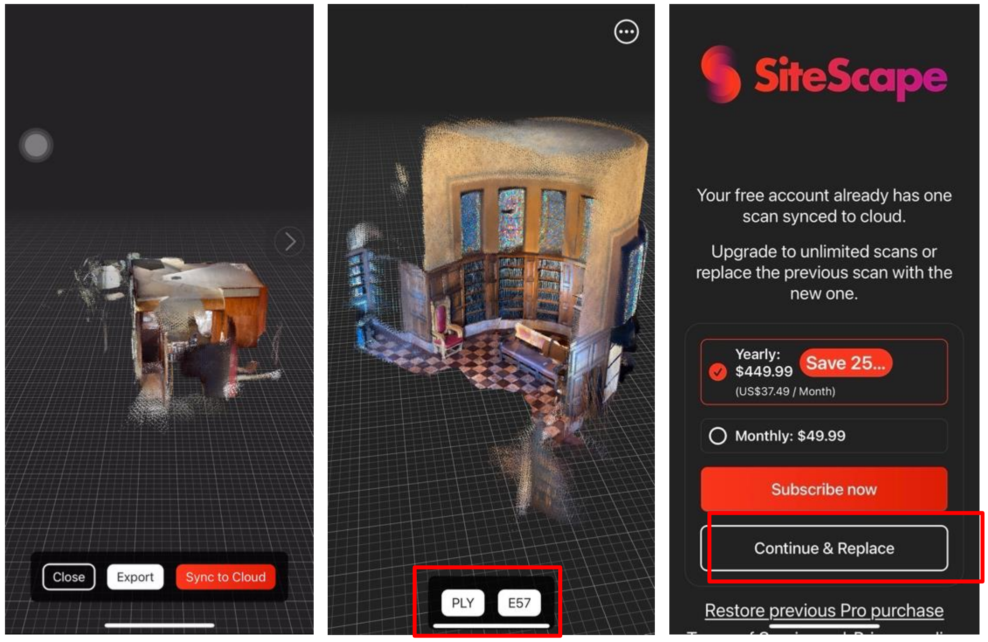


Figure 4-13, 4-14, and 4-15: SiteScape post scan exporting and synchronizing

g) Repeat process 2. a) – f) on abutting structures until cover the entire interior and exterior.

Method B: With Tripod

a) Select a tripod standing point; keep at least 3 feet away from the scanning target. Stable the smartphone on the tripod.

b) With the smartphone vertical, tap circle button to start scanning. Once started, the camara view will be turned off (Figure 4-16 and 4-17).

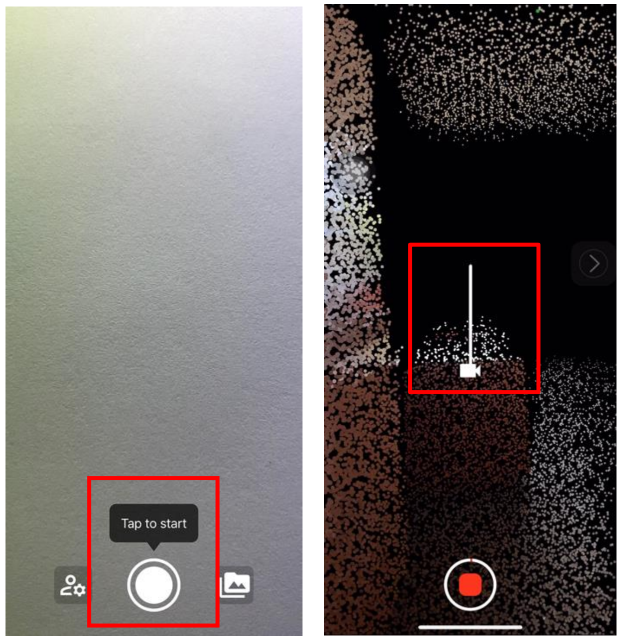


Figure 4-16 and 4-17: SiteScape operation interface and camera view adjust

c) Holding the smartphone, steadily rotate 360 degree to capture a horizontal loop of the room. Watch for points captured at the beginning of the scan, reduce overlapping those points when stop. During the acquisition process, move with the camera to avoid being captured in the scan. After a horizontal 360 degree scan finished, click circle button, then complete.

d) Change the angle of the smartphone; this can be achieved through using high-end tripod with a fluid head, or a regular tripod with carful operation. A 360 rotation capture has to be conducted twice, one with the smartphone camera taking an approximate 30% angle facing up, and one with the camera with an approximate 30% angle facing down (Figure 4-18, 4-19, and 4-20).

Figure 4-18: The smartphone device on tripod with an angle facing down

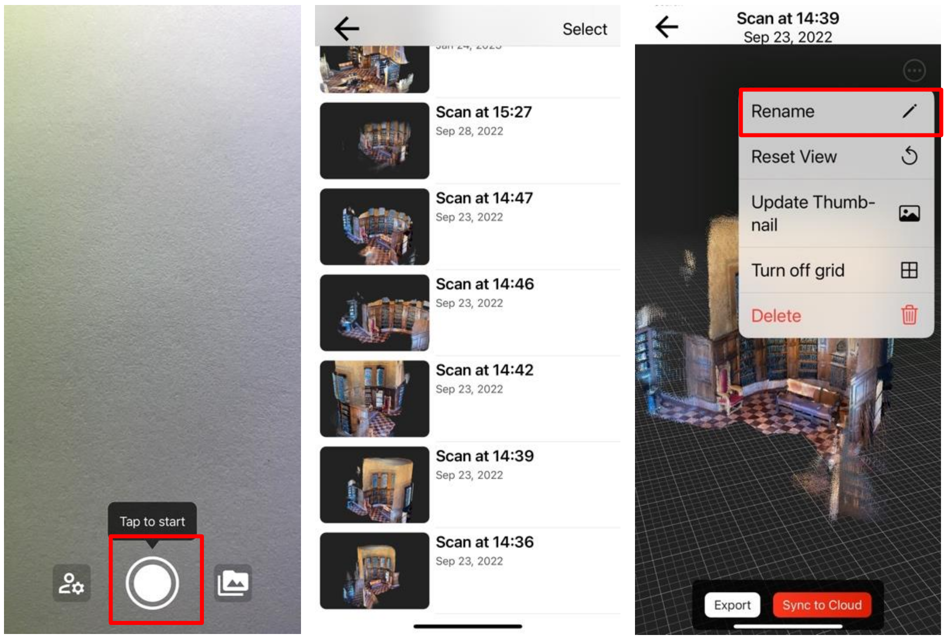
Figure 4-19 and 4-20: Tripod angled up and down

e) Repeat process Method B a) – d) on abutting structures until cover the entire interior and exterior. Tripod standing points should have overlapped area for registration process. In narrow space, the standing points should be closer to each other.

III. Save and Export

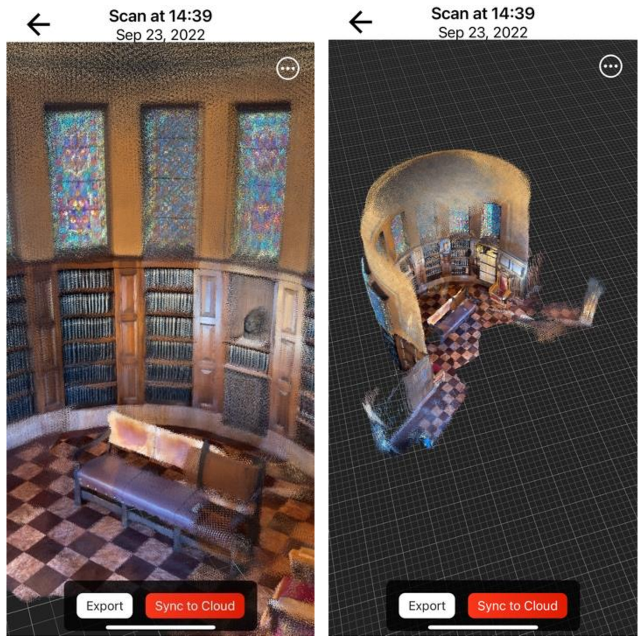
After finishing the scan, researchers should rename, sav,e and export files to usable format so further data process can be done.

a) Select the scan model from the library, click on the Option button, and Rename the scan data (Figures 4-21, 4-22, and 4-23).



Figures 4-21, 4-22, and 4-23: SiteScape library and renaming file

b) Move scanned data around, zoom in and out with finger, check for holes, missing parts, and double layers (Figures 4-24 and 4-25). A double layer is two layers of points describing the same surface (Figure 4-26). The two (or multiple) layers are created when an object is scanned or appeared twice in scanning range. Even though the layers of points are describing the same surface, the geometry might be accurate and repeated, the location of layers can various. The same information in different location causes data to be inaccurate and unrecognizable.



Figures 4-24 and 4-25: Zoom in and out scan of Hoose Library of Philosophy on SiteScape

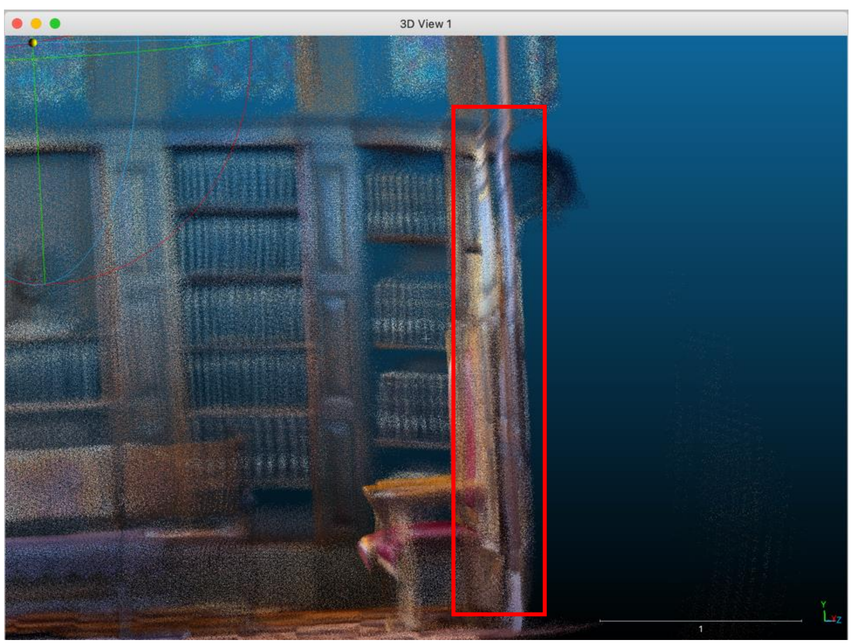
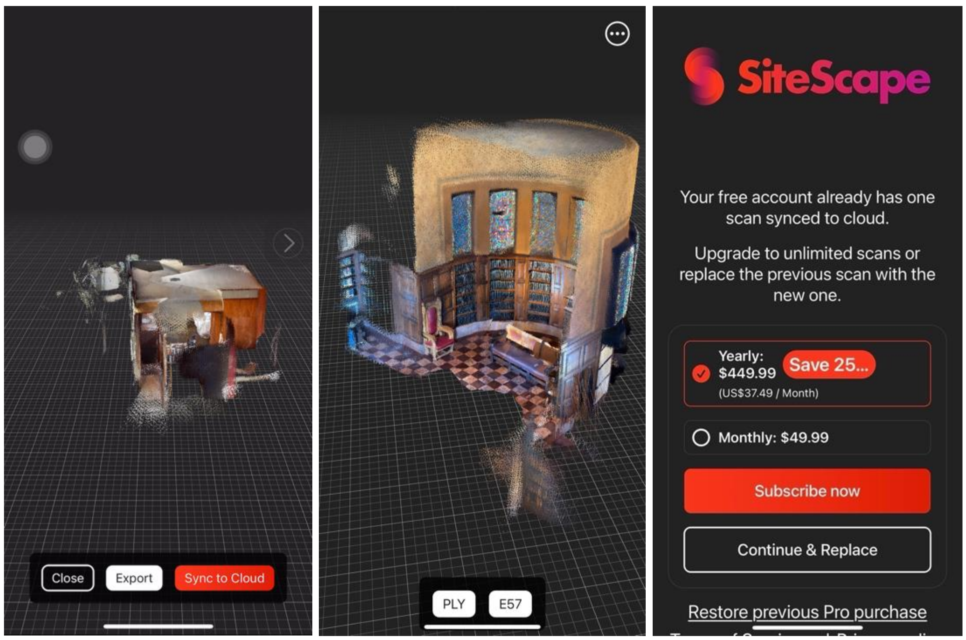


Figure 4-26: Double layer of points in *scan 2*

c) If any miscapture is detected in b), improve the scan path and repeat step 2. A) to 3. B) to rescan.

h) Click on Export, select file format, share through other smartphone app, upload to third party social media or synchronized to cloud (Figures 4-27 and 4-28,). Click on Continue & Replace if using free account (Figure 4-29). SiteScape offers PLY and E57 format for exporting, while common mesh model is not supported.



Figures 4-27, 4-28, and 4-29: SiteScape post scan exporting and synchronizing

4.1.2 Smartphone scanned data usage

3D point cloud data can be used in heritage conservation documentation in a variety of ways. For example, it can be used to generate 2D screenshots from 3D point clouds, which can be used to create detailed maps and diagrams of the heritage site. Additionally, 3D point clouds can be used to generate 3D models of the heritage site, which can be used to create virtual tours and interactive experiences. Finally, 3D point clouds can be used to take measurements of the heritage site, such as the size and shape of buildings, monuments, and other features. This data can be used to create detailed records of the heritage site, which can be used to inform conservation efforts.

Experiments done in overlapping point clouds with CloudCompare can be found in Appendix B.

4.2 Smartphone scanning overview and directions for site survey

The app used for the data acquisition process is SiteScape. The app offers two parameters: point density and point size. Point density determine the number of points describing the space, and point size only impacts the visualization but not the data. Depending on the size of site and the level of detail needed, point density can be selected from low-medium-high. In order to scan a larger area, a low level of point density was selected.

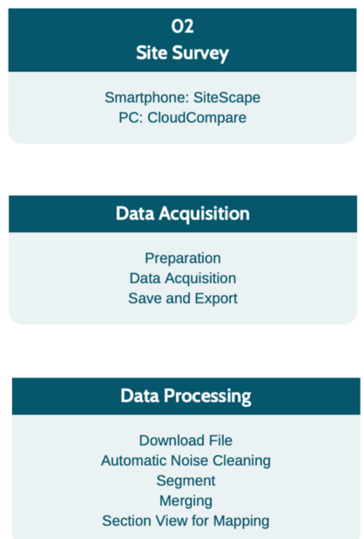


Figure 4-30: Heritage conservation survey by smartphone workflow diagram

4.2.1 Data acquisition

Multiple scans with the same parameter were conducted with an iPhone 13 Pro. Each scans share an overlap area for registration. In the test scans, parameters were set to high point density. The space was digitized from right to left, including the floor and ceiling. The same scanning path and setting guarantee the minimum difference caused by human factors in the comparison process.

During scan, mis-registration can be avoided through keeping more features in screen. Plain surfaces can cause LiDAR sensor mistakes in registration and acquisition.

I. Preparation

Before conducting scans, software, registration, and parameters should be prepared.

a) Repeat 4.1.1 I. Preparation, set point density to Low and point size Low.

II. Data Acquisition

The data acquisition process remains the same as smartphone acquisition for heritage conservation documentation. For the purpose of survey, multiple scans of abutting area are required.

a) Two scans will be conducted repeating 4.1.1 II. Data Acquisition with method A or B
b) Scan maximum area in one scan, when conducting the next scan, ensure areas of overlapping.

III. Save and Export

Post scan procedures including rename, save, and export.

a) Repeat 4.1.1 III. Save and Export.
b) Save and rename scans.

4.2.2 Data processing

Scanned data shall be downloaded to computer in PLY or E57 file format. The SiteScape webpage (https://app.sitescape.ai/projects) can be used to show the point cloud in digital 3D space. It has functions such as automatic registration with metric or imperial system, floorplan, measurements, and download.

The number of points obtained in a scan can be read at the right bottom of the interface. The built-in measurement tool accuracy is up to 0.1 inch.

For a space that cannot be captured in single scan, scanning files should be downloaded individually as PLY files and named systematically for data processing.

I. Download File

File can be exported from the smartphone to a computer for further data processing.

a) If the scanned data is synchronized to cloud, users can go to https://app.sitescape.ai/projects, log into SiteScape account (Figure 4-31).

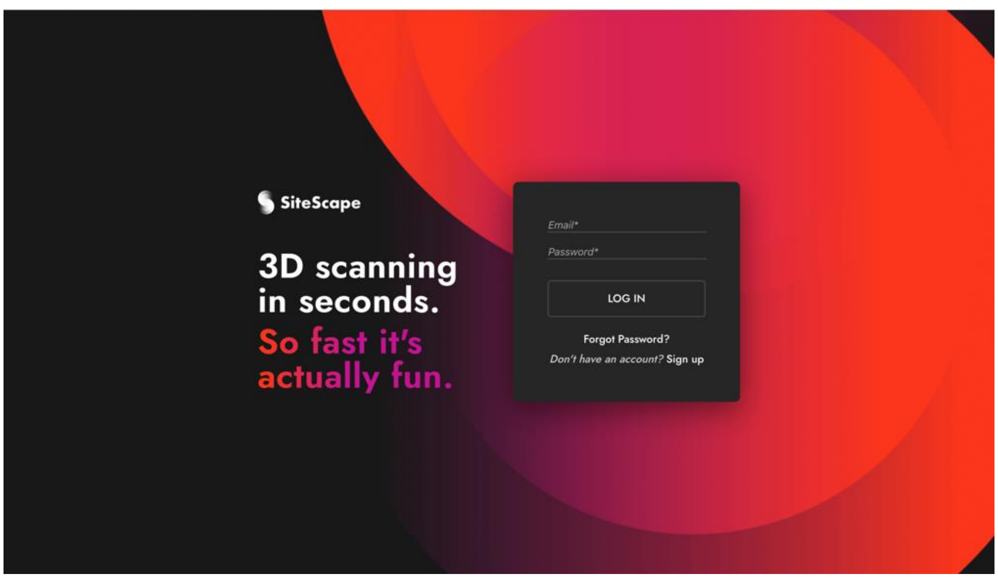


Figure 4-31: SiteScape webpage log in

b) On the website, users should see the synchronized file; click to open (Figure 4-32).

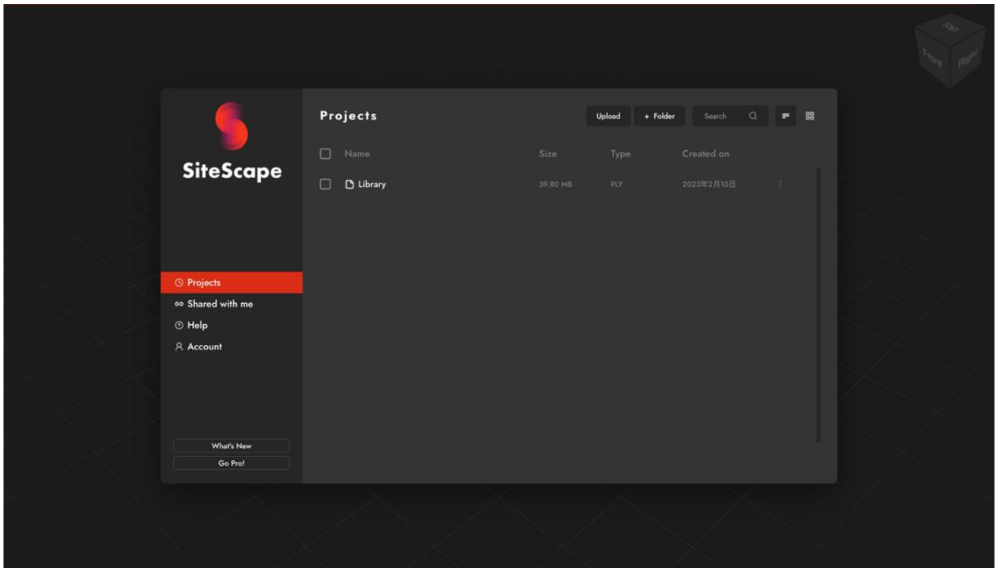


Figure 4-32: SiteScape project database

c) Use tools from SiteScape to measure, view floorplan, and change point size (Figures 4-33, 4-34, and 4-35).

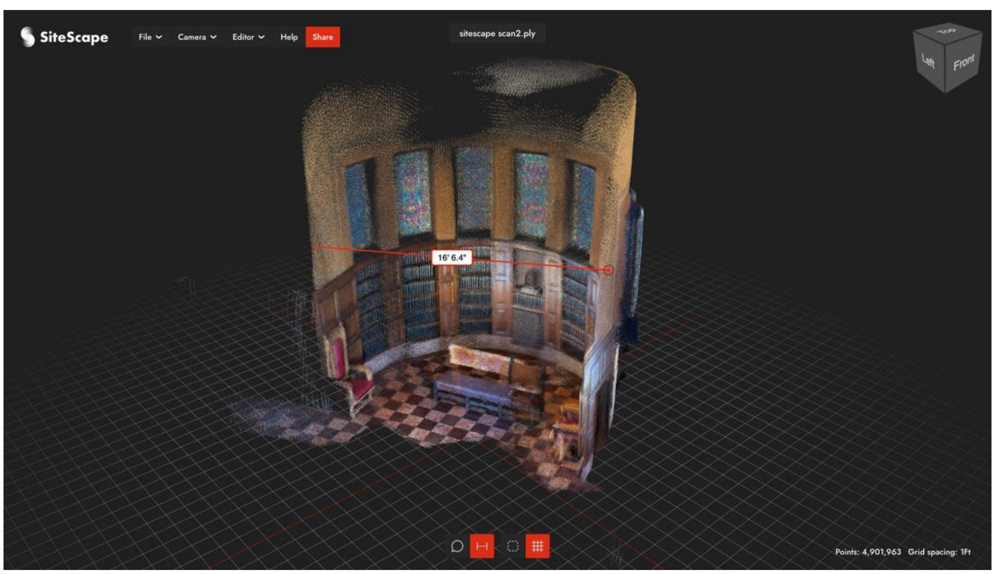


Figure 4-33: SiteScape measurement

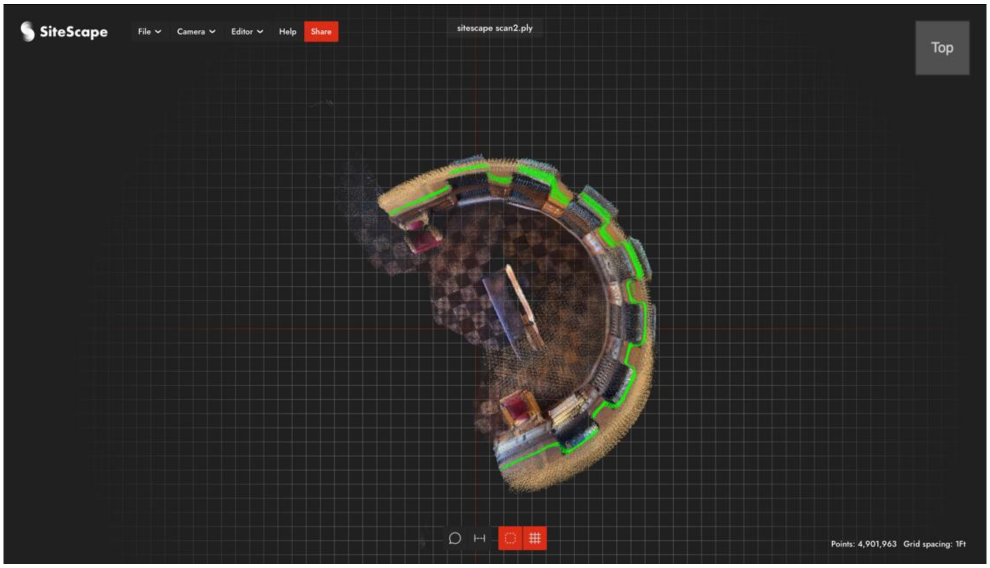


Figure 4-34: SiteScape floorplan

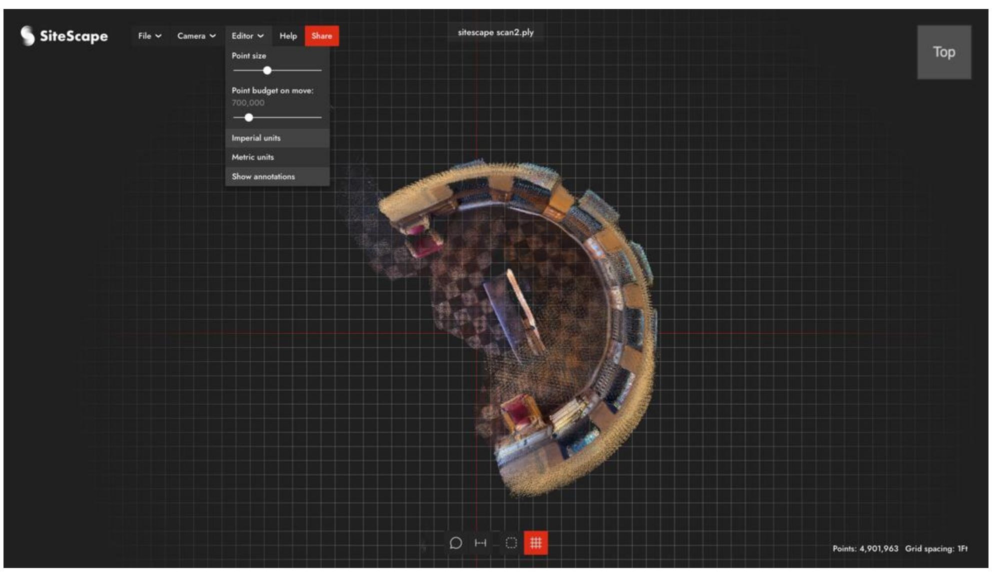


Figure 4-35: SiteScape change point size

d) If not synchronized to the cloud, download scanned data to a desktop computer, then opened in CloudCompare (Figure 4-36).

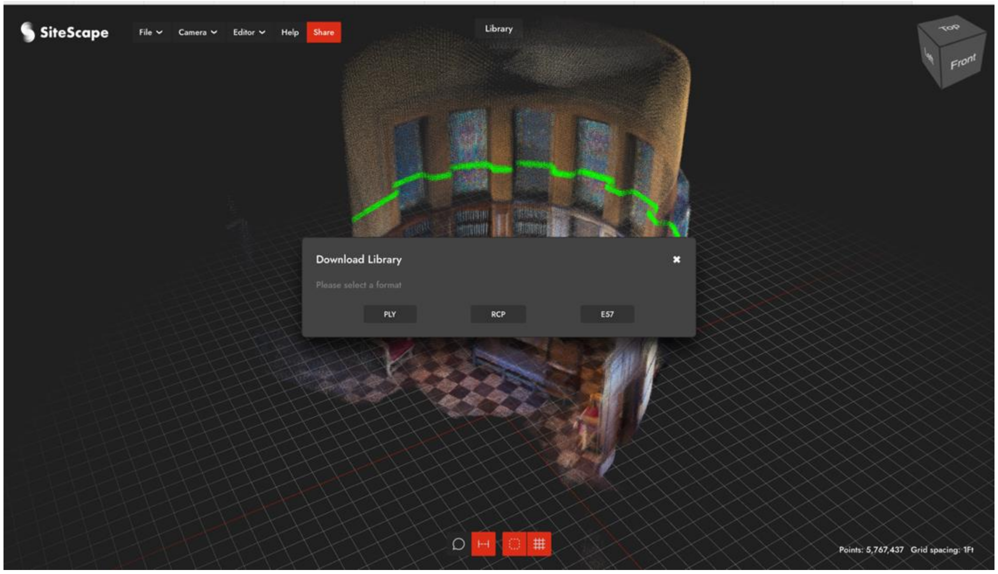


Figure 4-36: Download options from SiteScape webpage

e) Click File-Open, change file format to PLY mesh, select the scan file, and open in CloudCompare. When Ply File Open window pop up, click Apply all (Figure 4-37).

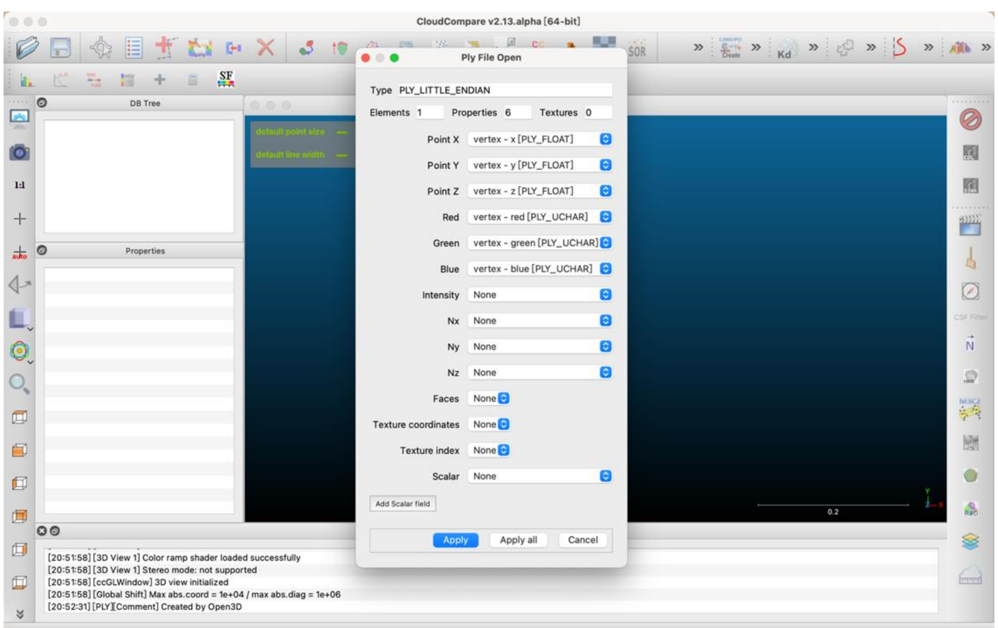


Figure 4-37: Open file in CloudCompare

II. **Automatic Noise Cleaning**

To reduce the fuzziness of scanned data, an automatic noise cleaning process will be completed through adjusting following parameters:

a) Open the scan file in CloudCompare. Select the cloud in the DB Tree Window. The DB Tree Window is the menu on the left (Figure 4-38).

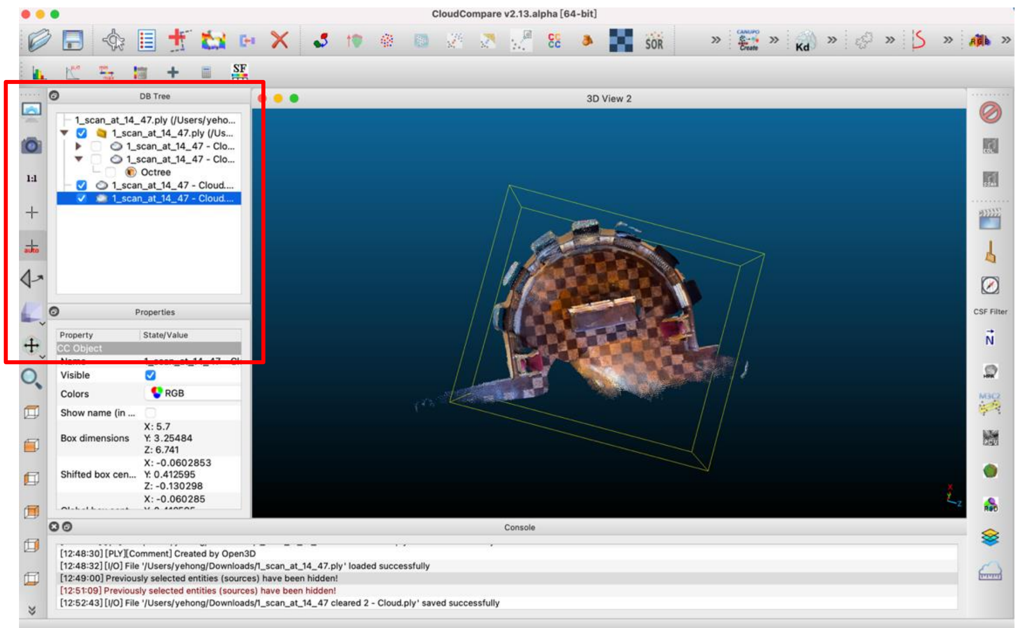


Figure 4-38: Select the cloud in DB Tree window

b) Filter out floating point by clicking on the SOR icon  on the tool bar and adjust the "Standard deviation multiplier threshold" to 2.5. A new file will then be created by the software (Figure 4-39).

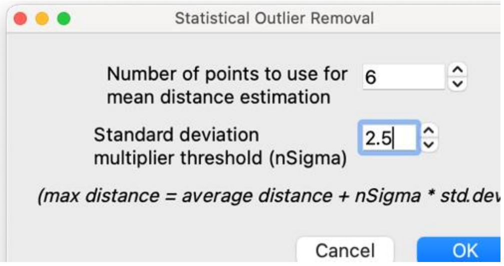
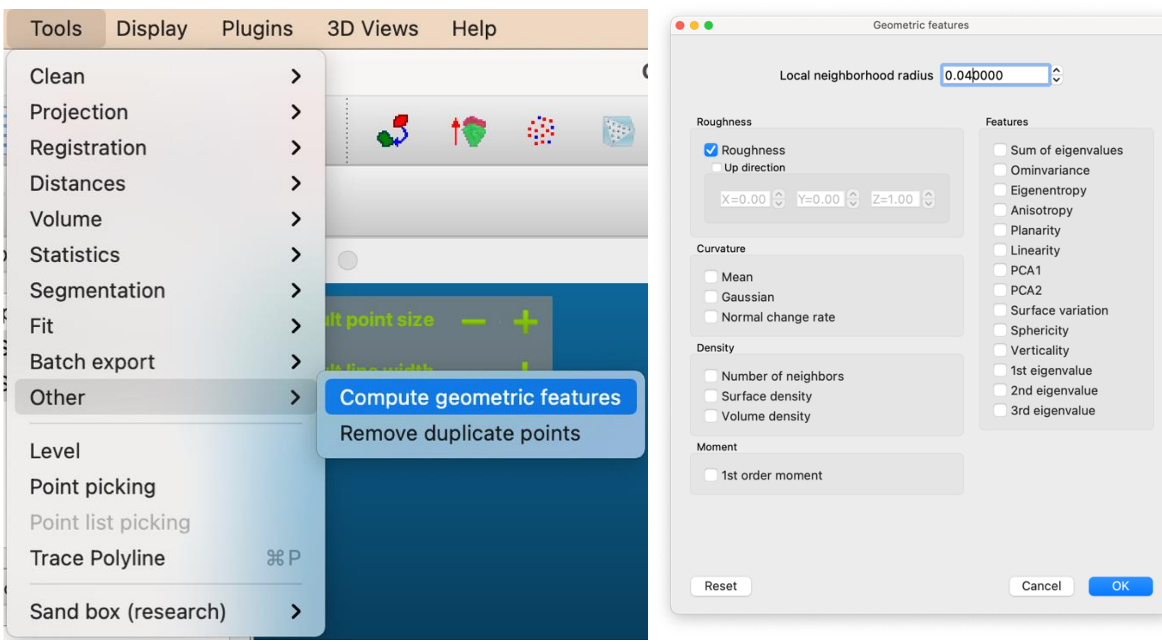


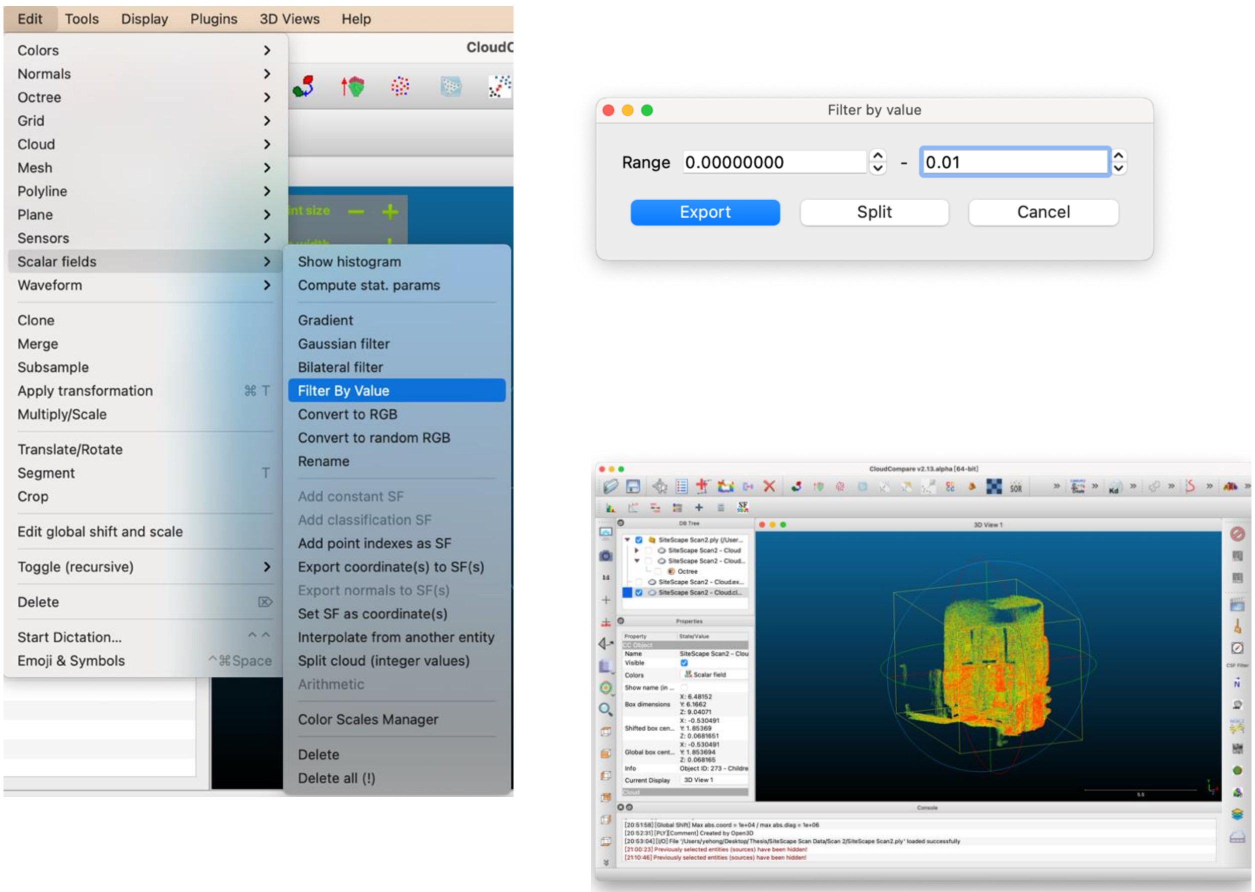
Figure 4-39: SOR (Statistical Outlier Removal) setup

c) Select the filter file by using Tool – Other – Compute Geometric features; select “Roughness” then adjust Local neighbor radius to 0.04. click OK (Figures 4-40 and 4-41). A scalar field will be created. A scalar field is simply a set of values. As each value is associated to a point it is possible to display those values as colors or to apply filters on them.



Figures 4-40 and 4-41: Compute geometric feature and settings

d) To clean up scans, go to Edit – Scalar fields – filter by value, setting the range from 0 to 0.01, and export (Figures 4-42 and 4-43). A new file with the cleaned-up scans can be exported by clicking the save icon. Color mode can be changed from Properties – Colors – RBG or Scalar filed (Figure 4-44).



Figures 4-42, 4-43, and 4-44: Filter by value, settings, and change color

III. Segment

The segment tool is used to crop point cloud data and remove unwanted points.

a) Click on the scissor icon  for segment, left click to frame the data with green contour lines, right click to finish framing (Figure 4-45).

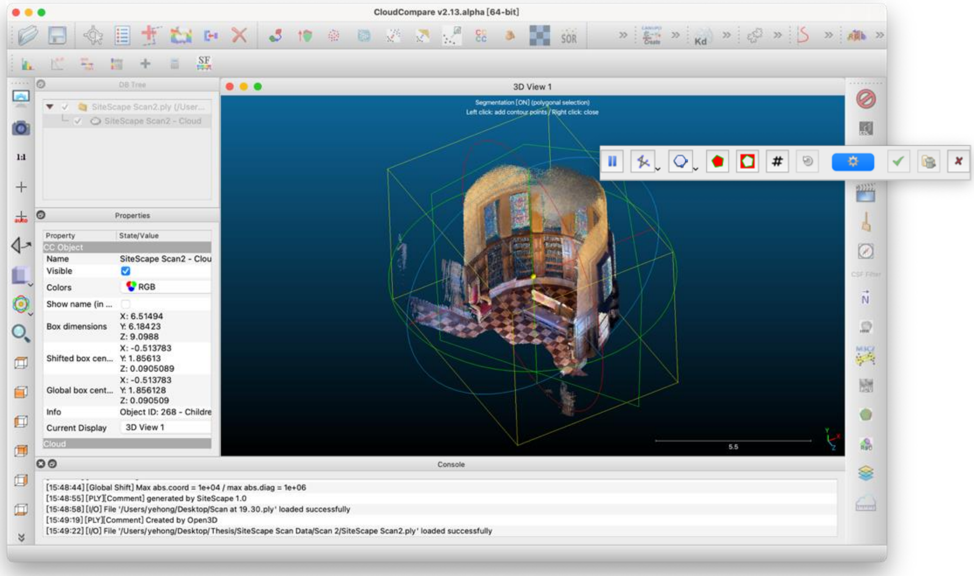
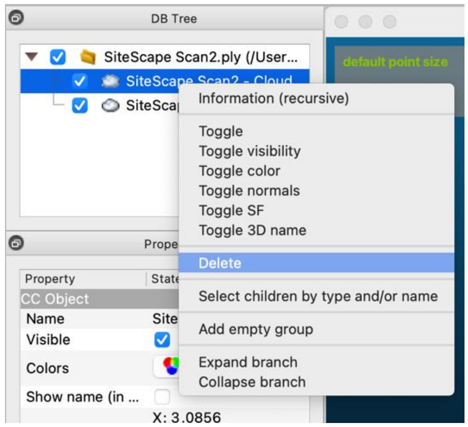


Figure 4-45: CloudCompare Segment tool

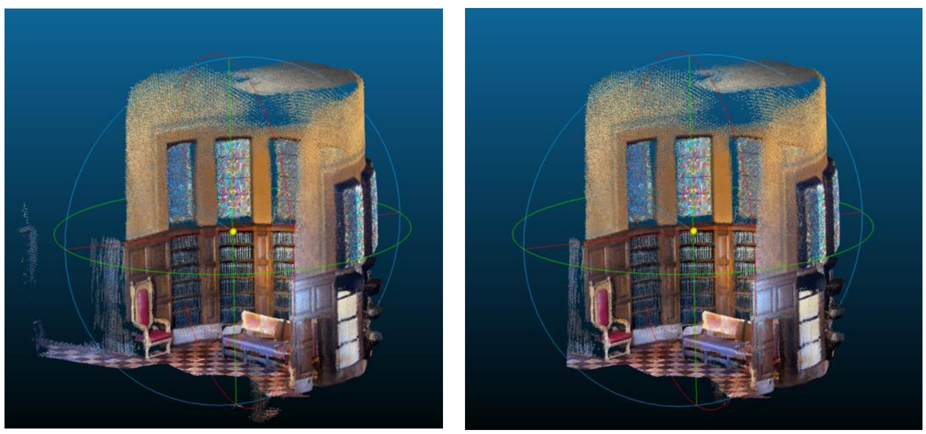
b) Click on the button with a pentagon in red to remove unwanted points outside the frame. Then click the green check button to finish (Figure 4-46).

Figure 4-46: Segment tool bar

c) In DB Tree view window, check and uncheck unwanted part to see before and after cropping. Select the cloud of unwanted parts and delete (Figures 4-47, 4-48, 4-49).



Figures 4-47: Delete unwanted part



Figures 4-48 and 4-49: Before and after segmenting

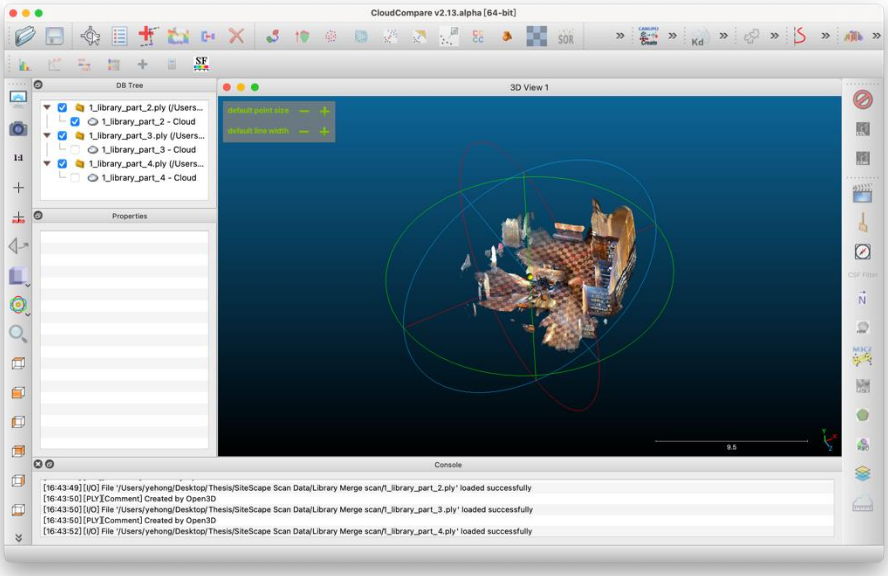
d) Save the point clouds and rename the file.

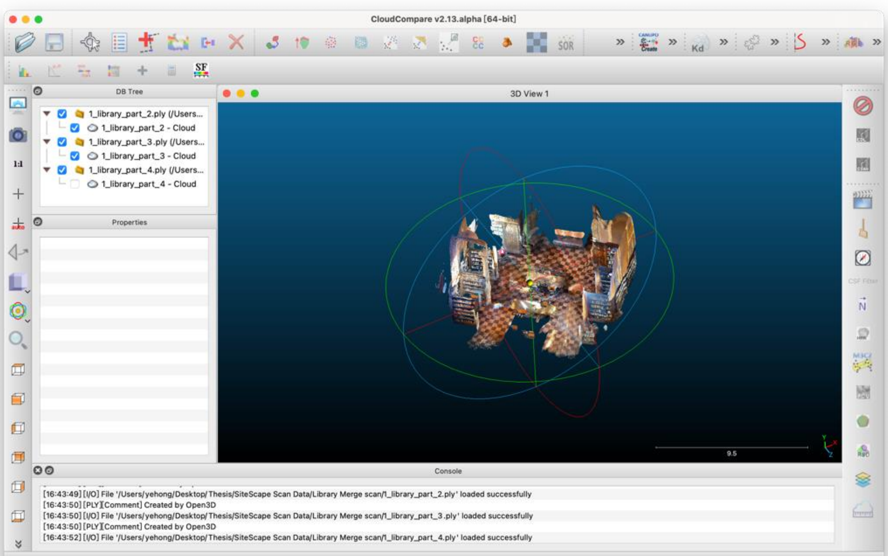
Apply automatic noise clean and segment to all individual scans.

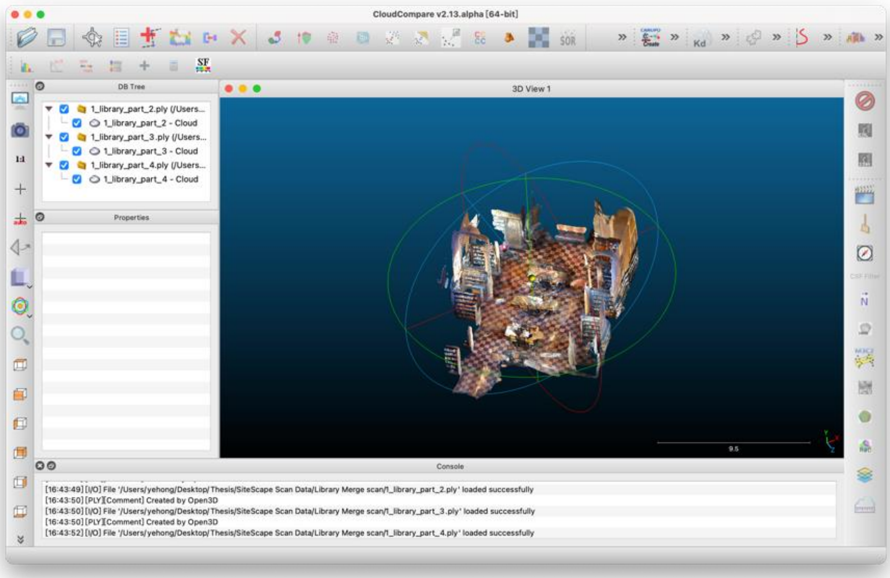
IV. Merging

The Merging tool in CloudCompare is used to piece multiple individual scans together in generating a larger floorplan.

a) Open all cleaned files in CloudCompare. The scans will be registered automatically (Figures 4-50, 4-51, and 4-52).

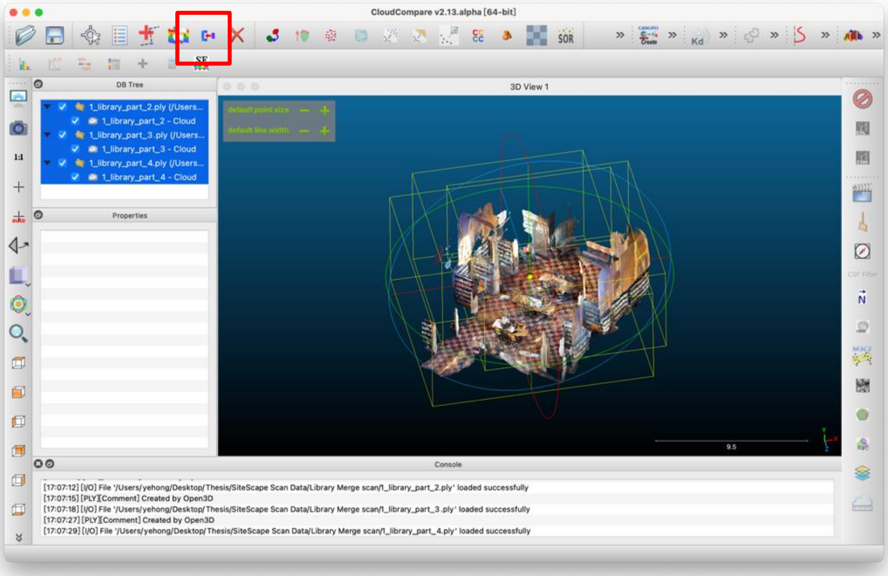


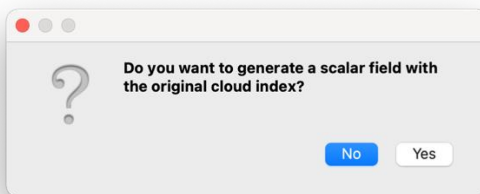




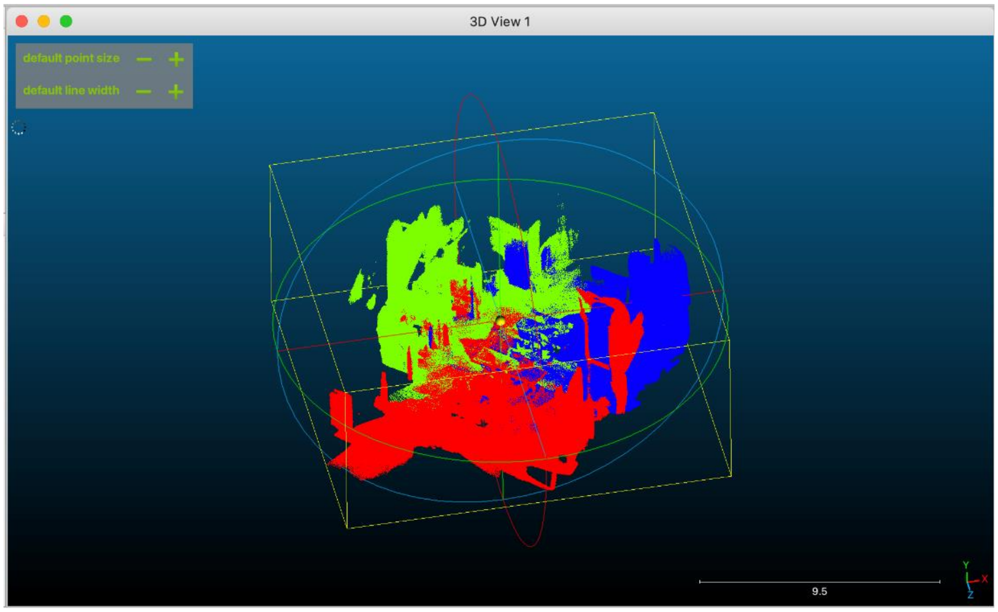
Figures 4-50, 4-51, and 4-52: Point clouds automatically registered and merged

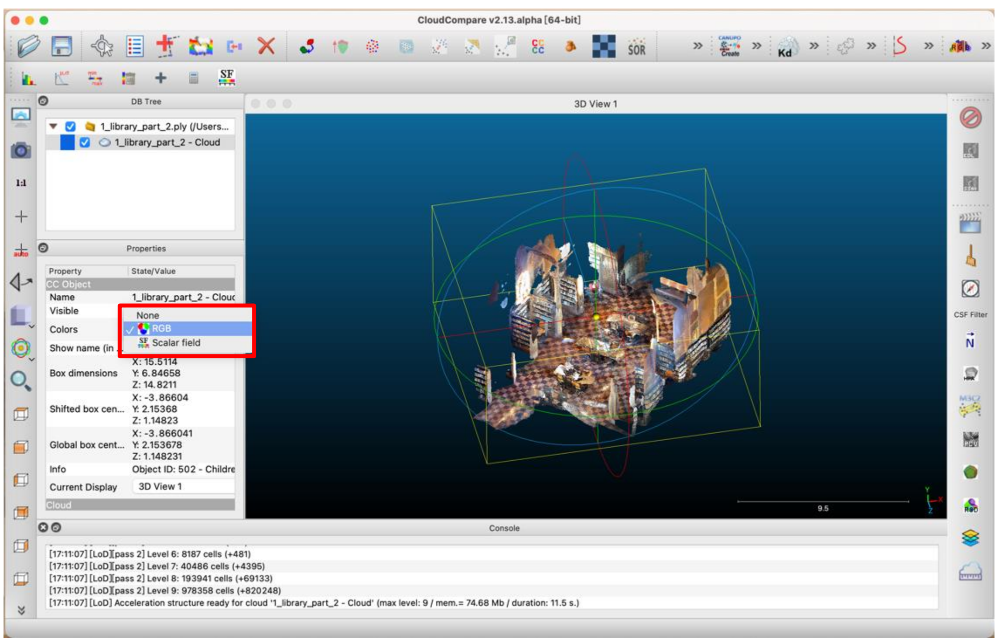
b) Scans will automatically registered and linked. Select all file in DB Tree window and click on merge multiple scans button on tool bar (Figure 4-53). Click yes to question window (Figure 4-54). A new merged file will be created (Figure 4-55). Scans will be show in different color for distinguish. To view color mode, change in Properties – Color – RGB/Scalar field (Figure 4-56).





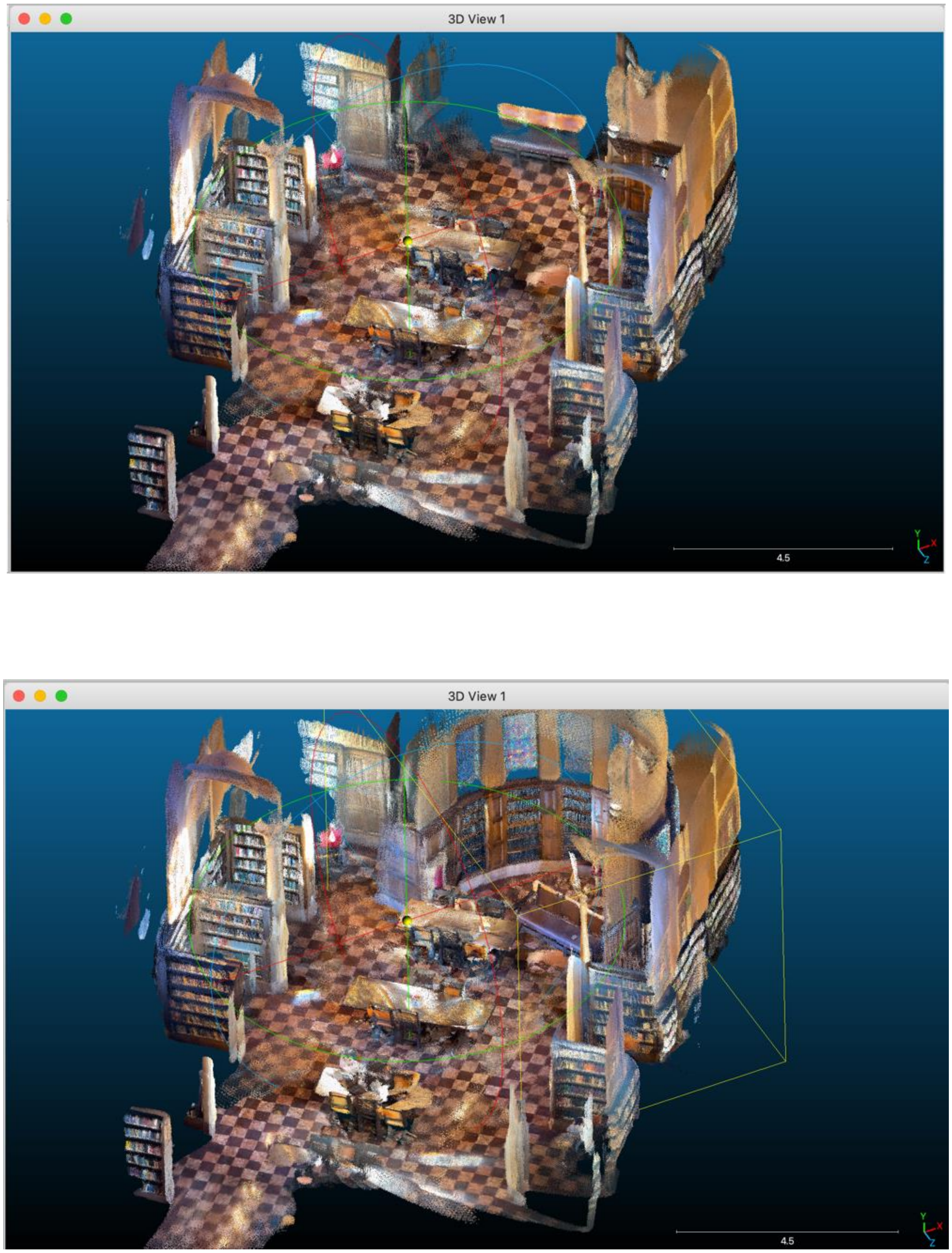
Figures 4-53 and 4-54: Select all point clouds and merge





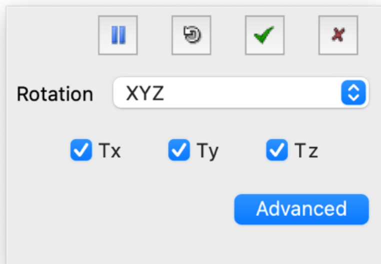
Figures 4-55 and 4-56: After merge view in scalar field and how to change to RGB color

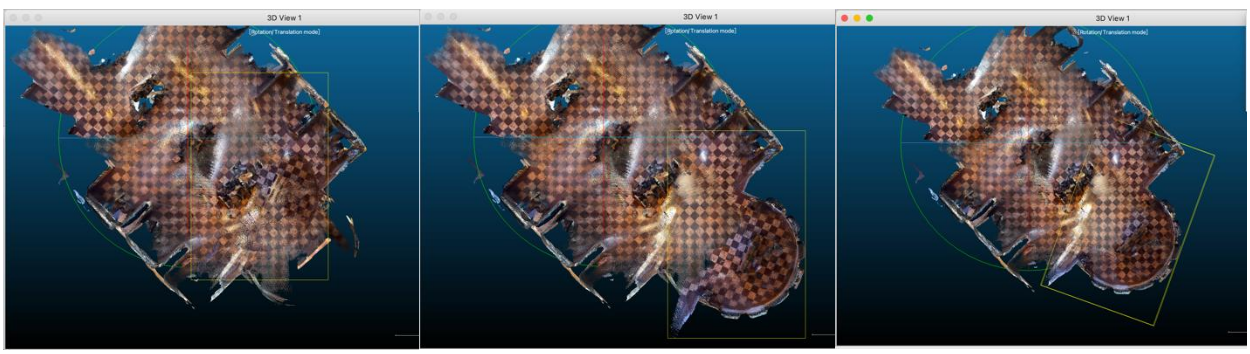
c) Sometimes scans acquired from different time may be registered to the wrong place (Figures 4-57, 4-58). In this case, users can adjust the scan with manual method or tool align two clouds by picking four points.



Figures 4-57 and 4-58: Example of mis-registration of point clouds

d) To manually register the scans, click on translate/rotation button . A point cloud can be moved in X, Y, and Z axis (Figure 4-59). Selected cloud will show in yellow box. Users can drag, rotate, and move the selected scan to match the existing combination through visual (Figures 4-60, 61, 62). The selected cloud was moved in all view direction. This method heavily relies on the operator's ability to edit the scan.





Figures 4-59, 4-60, 4-61, and 4-62: Translate/rotation setting, and manual alignment process

e) To register point clouds by picking points, users need to use translate/rotate function move the mis-registered scan away from the existing scan (Figure 4-63).

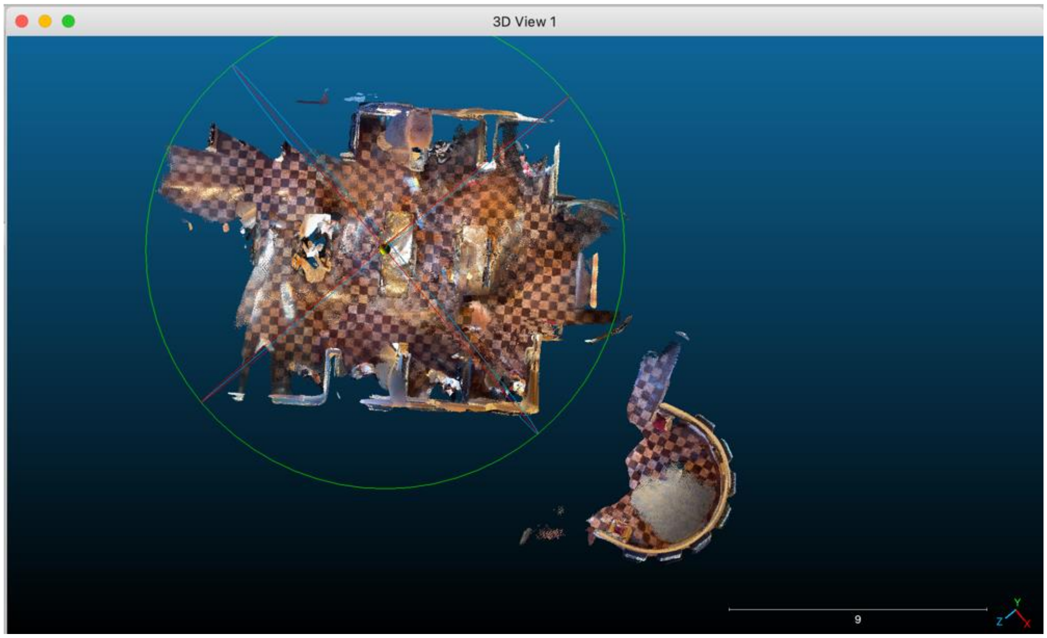
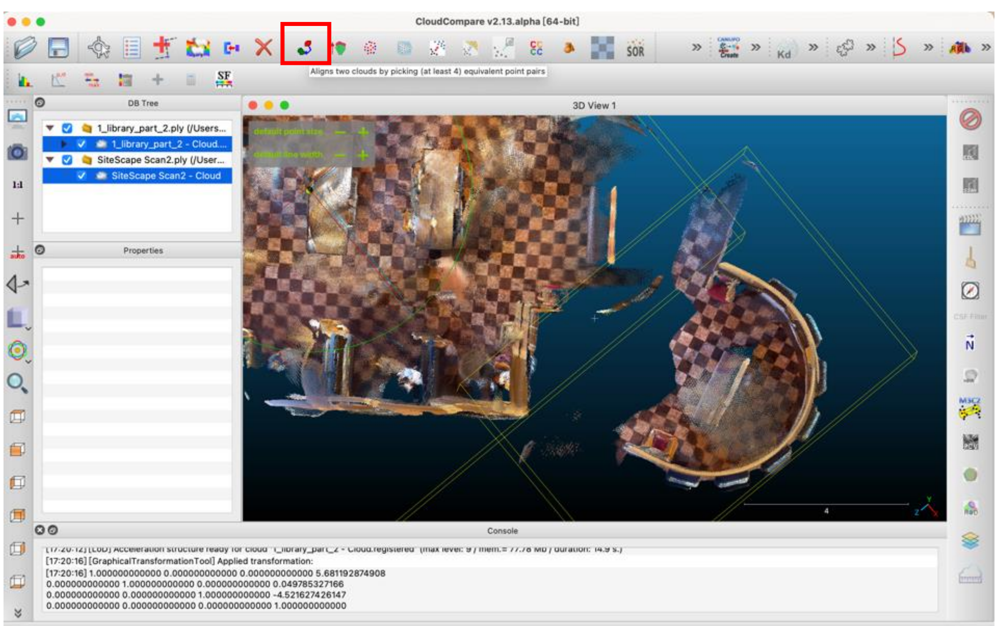
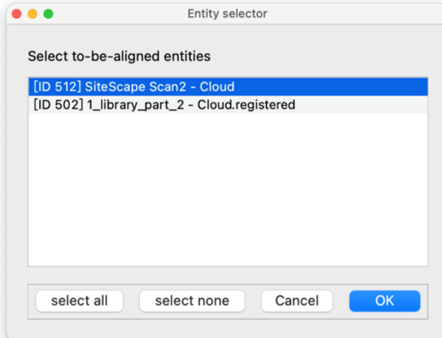
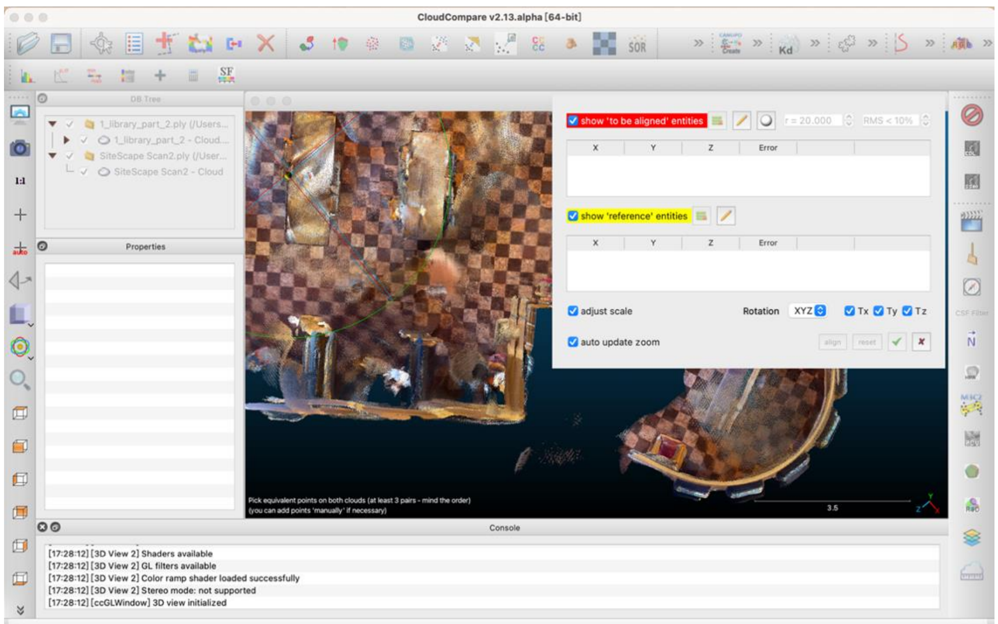


Figure 4-63: Move to-be-aligned point cloud away from reference point cloud

f) Select both scans, then click Align two clouds by picking four points button. Select the scan you want to align, and OK (Figures 4-64, 65, and 66).

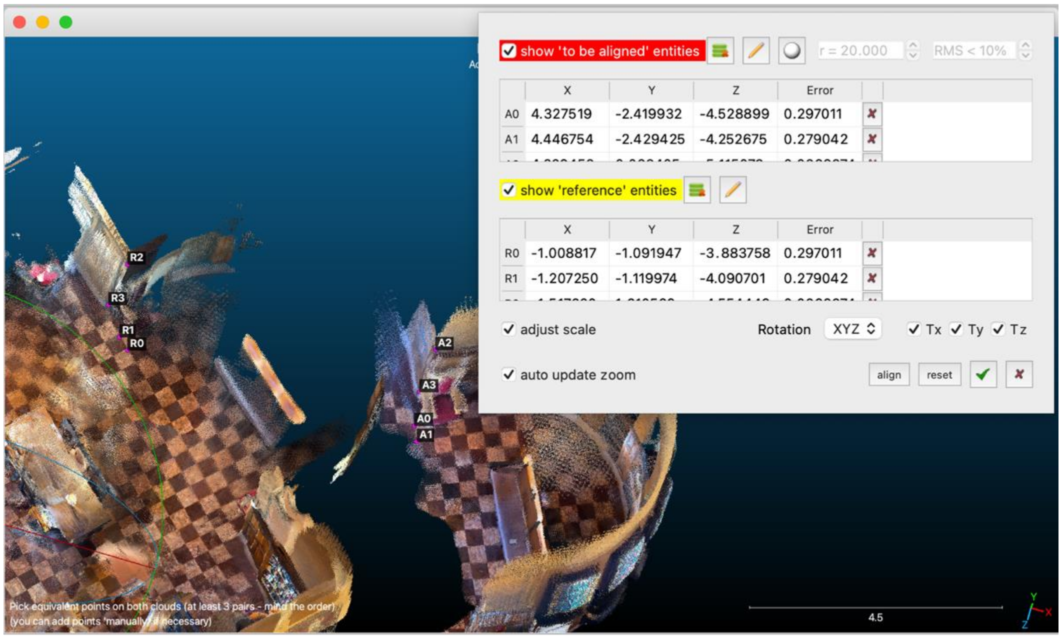


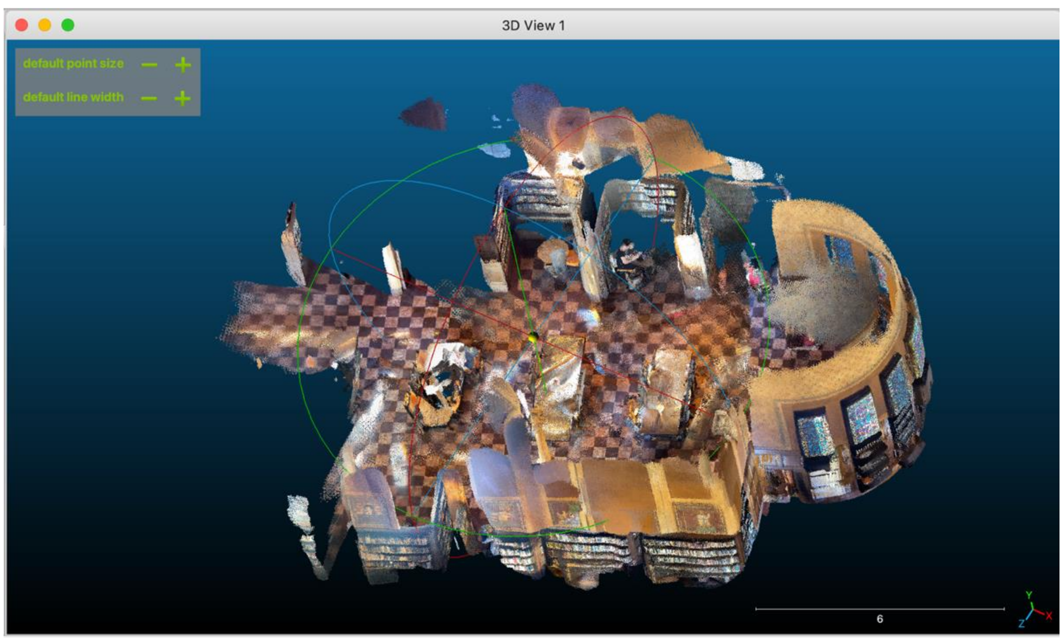




Figures 4-64, 4-65, and 4-66: Align two clouds by picking four points tool, select to-be-aligned entities window, and alignment interface

g) Pick at least three pairs of equivalent points on both clouds. Selecting points on vertical, horizontal and different planes, avoiding all reference points on the same flat surface, can help to create a more accurate align result (Figure 67). Click align, visual check if the scan is aligned correctly. If yes, click green check, if not, reset and reselect equivalent points (Figure 4-68).





Figures 4-67 and 4-68: Pick equivalent points on both to-be-aligned and reference entities, and align result

h) Select all files in DB Tree window. Click on merge multiple scans button on tool bar. Click yes to question window. A new merged file will be created. Scans will be show in different color for distinguish. To view color mode, change in Properties – Color – RGB/Scalar field (Figure 4-69)

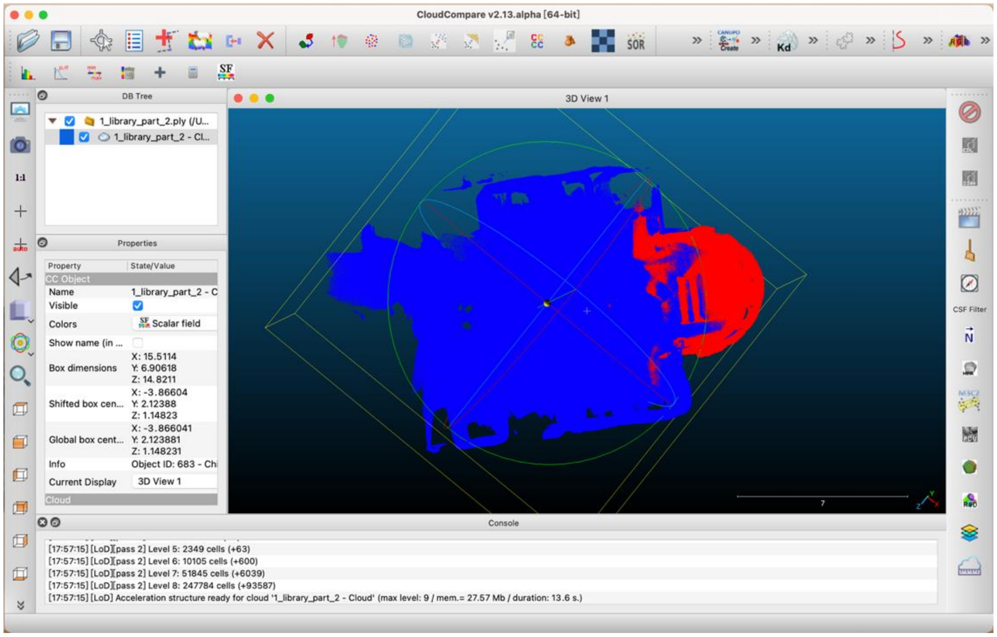


Figure 4-69: Merging result in scalar field

i) Save the file.

Section View for Mapping

Section view can be created to use as floorplan or map.

a) Change to the sideview with the perspective tools by clicking on cubs on the left tool bar (Figure 4-70).

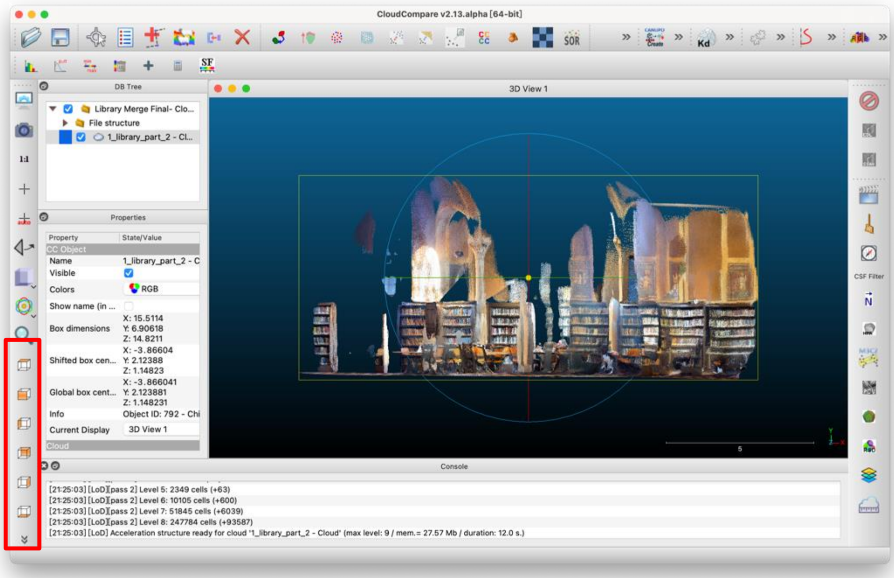
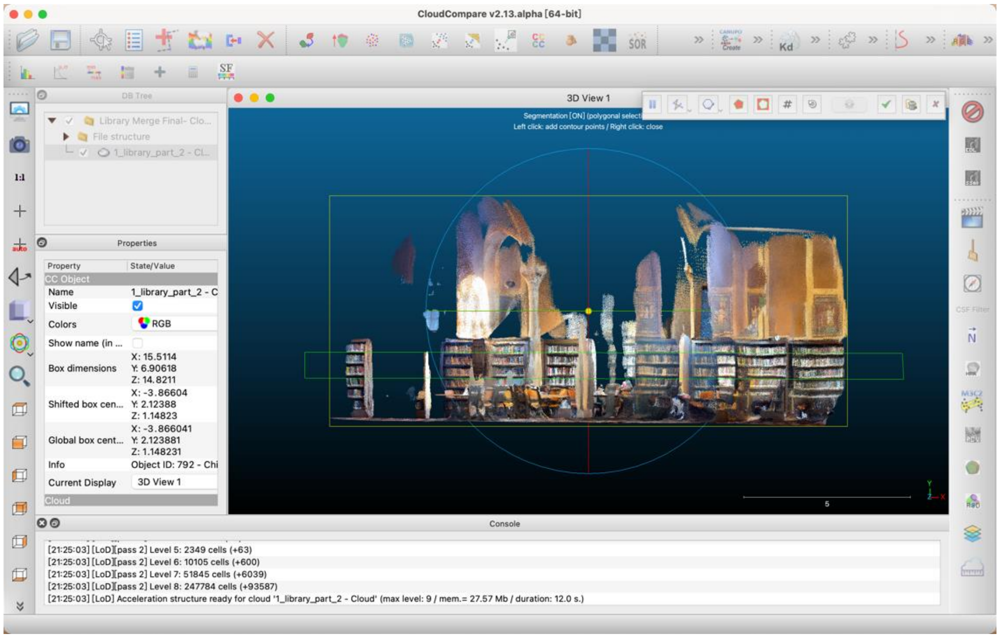
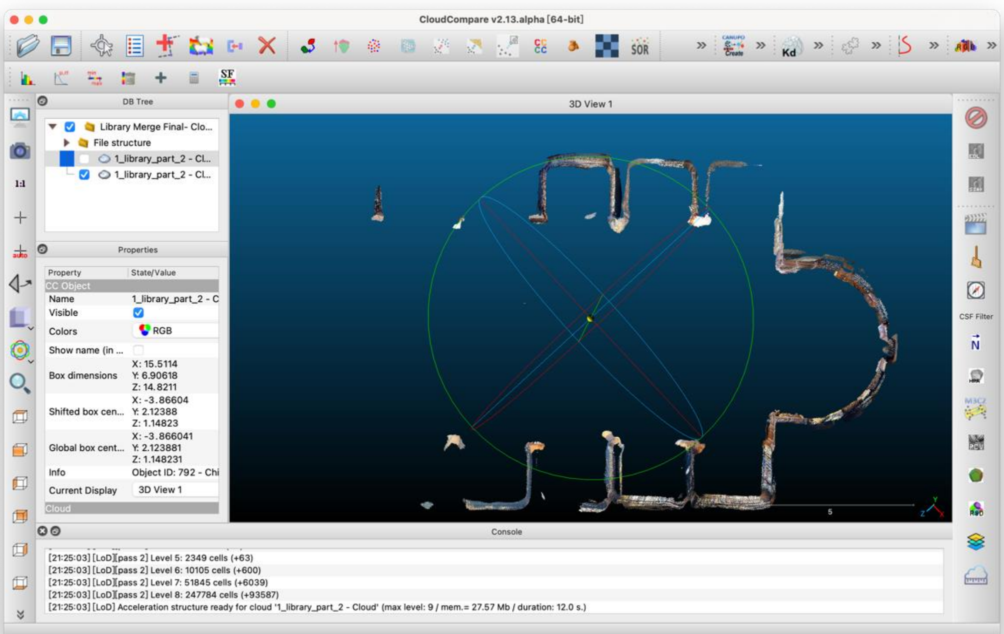


Figure 4-70: Merged library scans from sideview

b) Use the segment tool to create a horizontal slice for floorplan; then move to top view to see floorplan (Figures 4-71, 4-72).





Figures 4-71 and 4-72: Creating a slice of structure with segment tool, bird eye view of the floor plan

c) Users can export the floor plan file, to be traced over in AutoCAD, Revit, or other drawing software, or measure the floor plan through uploading the file to the SiteScape webpage for measuring distance.

4.3 Smartphone scanning overview and directions for monitoring

Non-destructive detection of building shifting requires monitoring of a building over several years. However, the test scan and case study were finished in a year, which does not provide enough time change to properly study this feature. Instead of monitoring changes over time, the accuracy of point clouds acquired by smartphone would be accessed. Different from the goal of site survey and documentation, monitoring a building need to validate the difference of two scans that described the same target. If smartphone captured data are stable and repeatable, they can be used for monitoring. If the difference between the two exact same scans overly various, researchers cannot determine the origin of deviation (from scan error/limitation or building movement).

The same physical space in the Hoose Library of Philosophy will be scanned with the same smartphone device and SiteScape twice. The two scans will be compared in CloudCompare. In the Chapter 5 case study, the methodology will have additional scan from a professional scanner, which will be considered ground truth.

4.3.1 Data acquisition

Two scans in same parameter setting were acquired with the device. In the test scans, parameters were set to high point density and medium point size. The space was digitized from right to left, including the floor and ceiling. The same scanning path and setting guarantee the minimum difference caused by human factors in the comparison process.

During scan, mis-registration can be avoided through keeping more features in screen. Plain surfaces can cause LiDAR sensor mistakes in registration and acquisition.

I. Preparation

Before conducting scans, software, registration, and parameters should be prepared.

a) Repeat 4.1.1 I. Preparation, set point density to Low and point size Low.

II. Data Acquisition

The data acquisition process remains the same as smartphone acquisition for heritage conservation documentation. For the purpose of survey, multiple scans of abutting area are required.

a) Two scans will be conducted repeating 4.1.1 II. Data Acquisition with method A or B
b) Scan with the same path or location twice.

III. Save and Export

Post scan procedures including rename, save, and export.

a) Repeat 4.1.1 III. Save and Export.
b) Save the two scans with the same scan path as *scan 3* and *scan 4*.

4.3.2 Data processing

Scans acquired from 4.3.1 were overlapped in CloudCompare to measure accuracy. Accuracy is described as the repeatability of scans. The cloud to cloud distance function in software was used for measure how close the points are to each other in repetitive scans. If the distance is small enough, the methodology can be proved valid. If the distance is overly big, the device and data cannot distinguish the change of building over years.

Before computing the distance between the two scans, they first have to be aligned in the software. The two scans were selected and computed with the finely registers already (roughly) aligned entities (clouds or meshes) function with parameters. Random sampling limit and final overlap percentage can be changed based on total number of points and the scanning difference between two scans. For example, *scan 3* compared to *scan 4* has fewer points describing the ceiling, which some points lack a point to align to. Thus the final overlap was left to 97% (Figure 4-73).

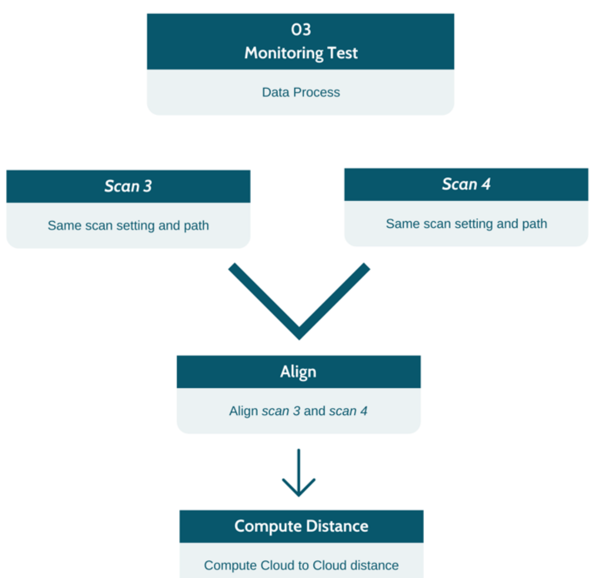


Figure 4-73: Monitoring data process work flow

I. Download File

Download smartphone scanned file for computer process.

a) Download scanned data in PLY file format to desktop; open CloudCompare (Figure 4-84).

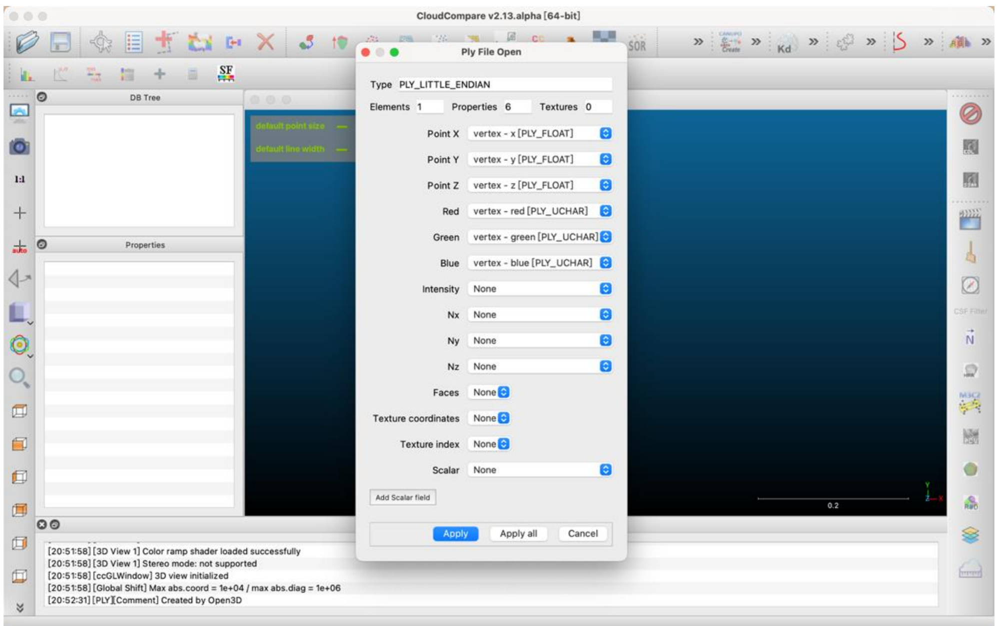


Figure 4-74: Open file in CloudCompare

b) Click File-Open, change file format to PLY , select the scan file and open in CloudCompare. By this step, the scanned data should be able to view in CloudCompare in point clouds.

II. Align Scans

Prepare two scans through CloudCompare aligning tools for distance computation.

a) Open both *scan 3* and *scan 4* (repeat of *scan 3*) in one CloudCompare window (Figures 4-75, 4-76).

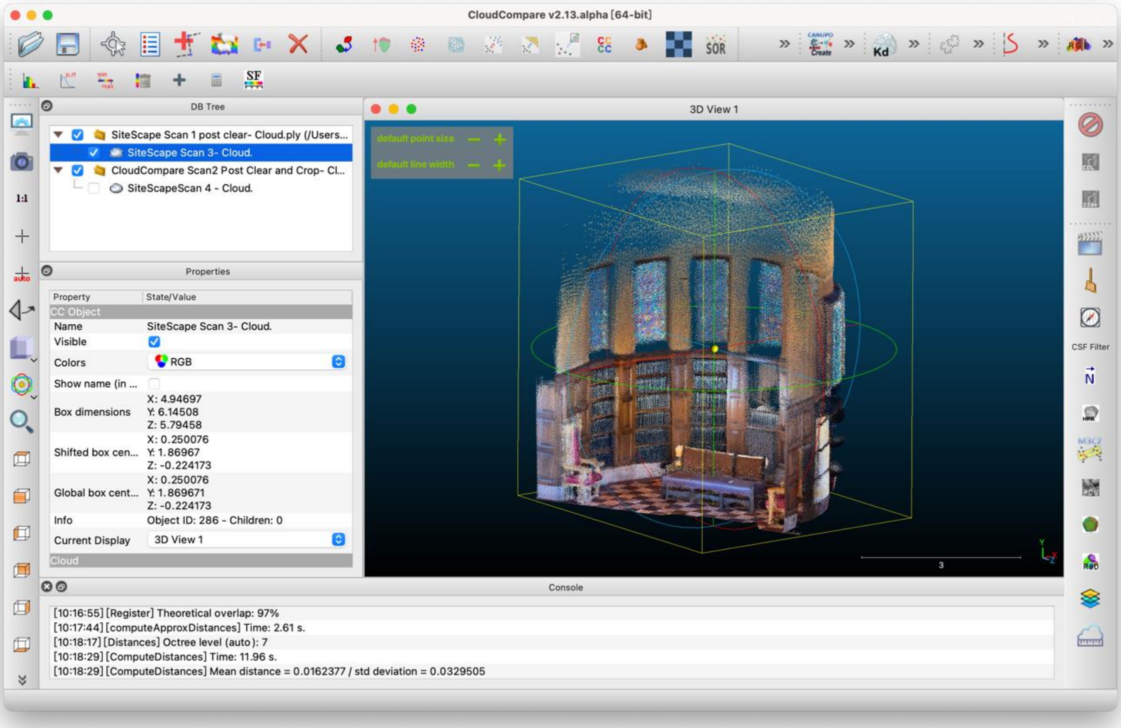


Figure 4-75: *Scan 3* point cloud in CloudCompare

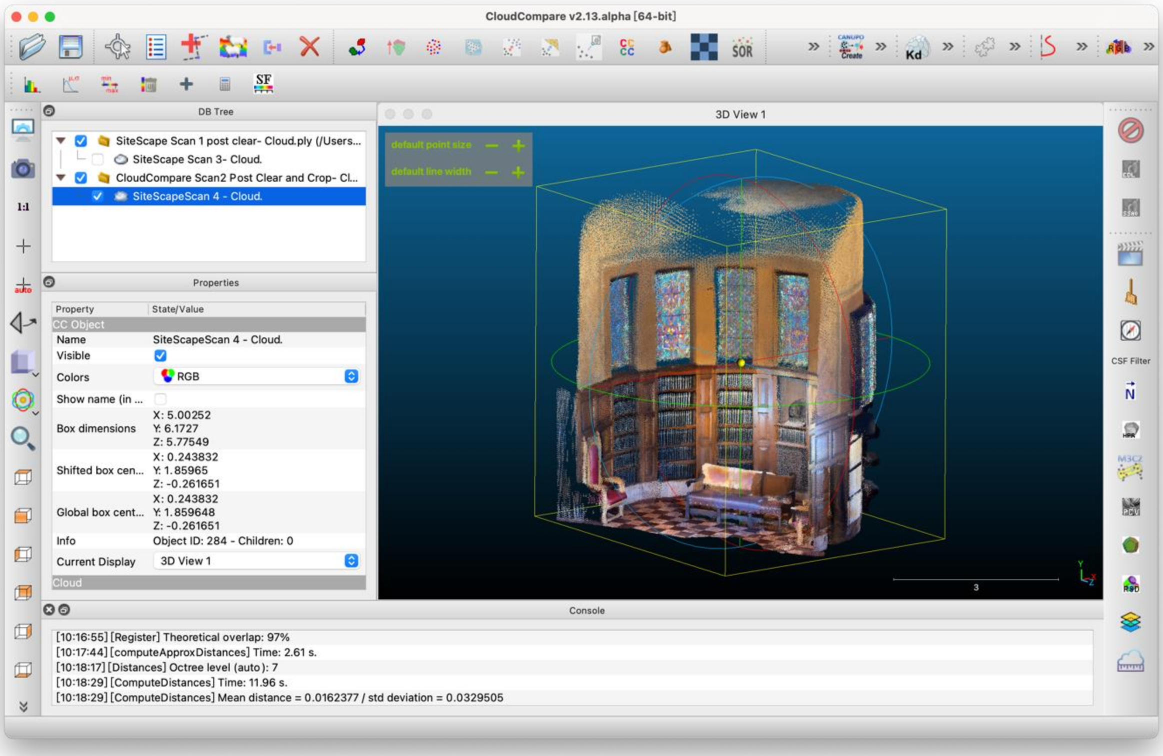


Figure 4-76: *Scan 4* point cloud in CloudCompare

b) Select both scans in DB Tree window, click finely registers already (roughly) aligned entities (clouds or meshes) button; then a clouds registration window will appear (Figure 4-77).

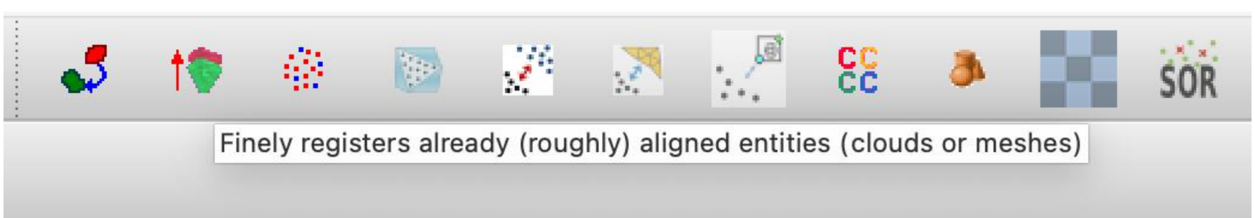


Figure 4-77: Finely registers already(roughly) aligned entities (clouds or meshes) tool

c) Click on parameters on clouds register window, adjust final overlap to 97%, and select adjust scale (Figure 4-78).

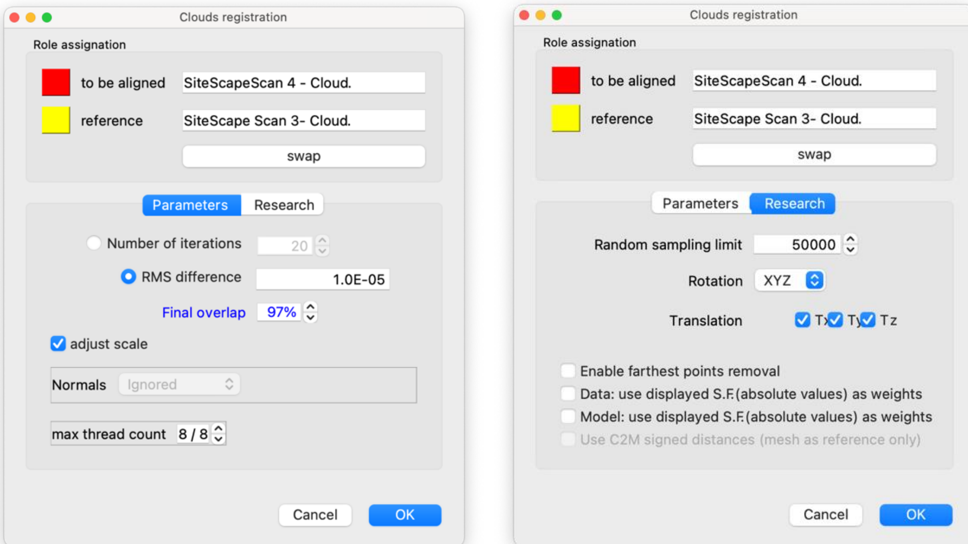


Figure 4-78: Cloud registration window setting

d) Click on research on clouds register window, adjust random sampling limit to 50,000, rotation to XYZ, and select all for translation, then click OK (Figure 4-79). The final Root Mean Square smaller than 0.5 represents a good result.

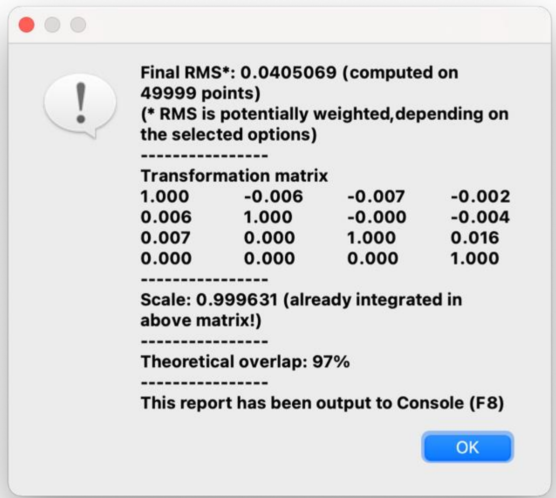


Figure 4-79: Result of aligning *scan 3* and *scan 4*

III. Distance Computing

The two-point clouds were compared respectively with following steps.

a) Select both scans in DB Tree window.

b) Click "Compute Cloud to Cloud Distance" icon on top tool bar, here *scan 4* is set as reference and *Scan 3* as comparison (Figure 4-80).

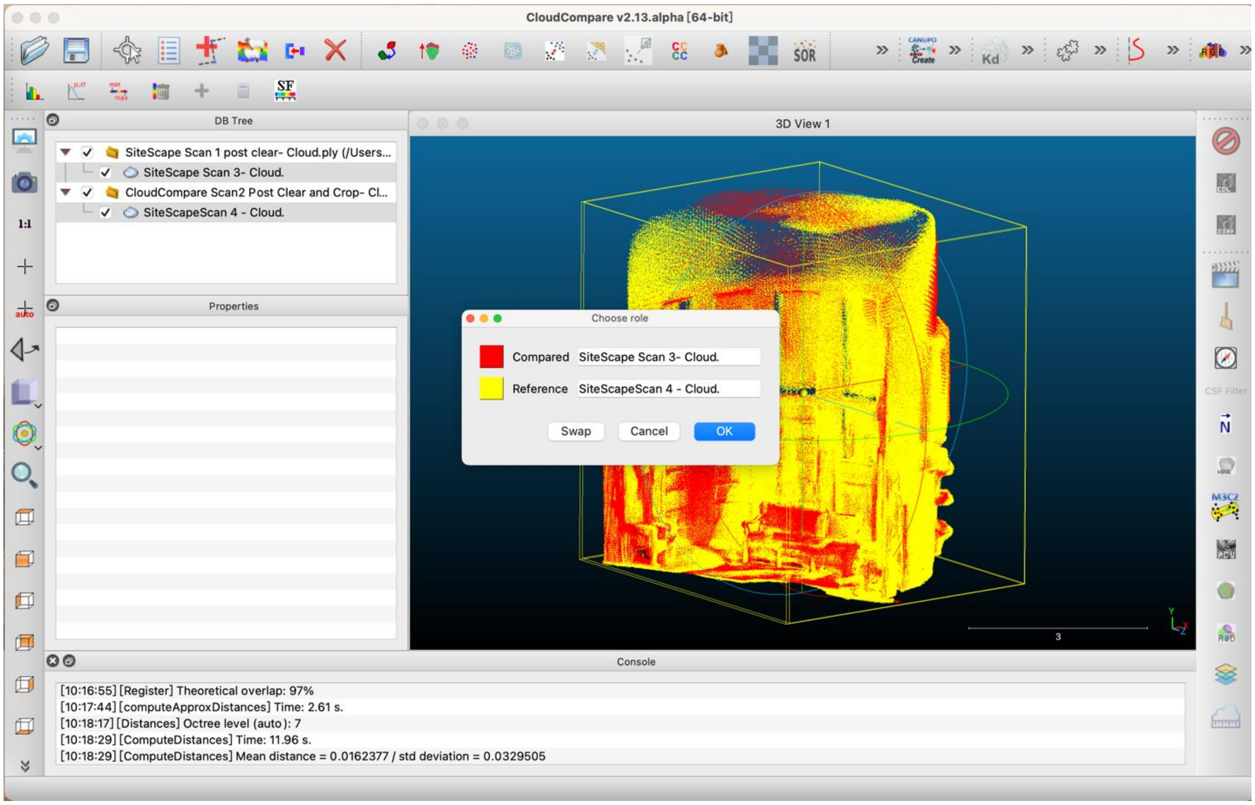


Figure 4-80, *Scan 4* as Reference and *scan 3* as Compared in CloudCompare cloud to cloud distance function

c) On the pop up window General parameter, select AUTO on Octree level, multi-threaded max thread count 8/8, Local modeling – None (Figure 4-81).

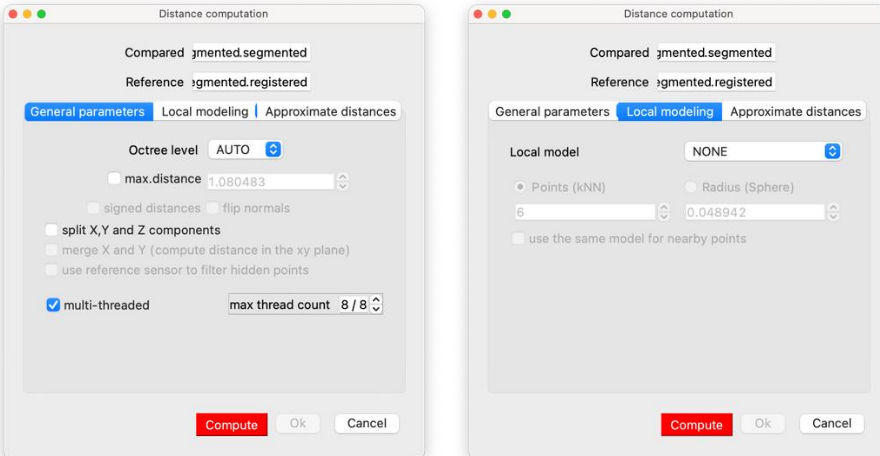


Figure 4-81: Distance computation parameter setup

d) On approximate distance window, click on the bottom right bar chart histogram, the chart will show the maximum distance and roughly estimated distance (Figure 4-82).

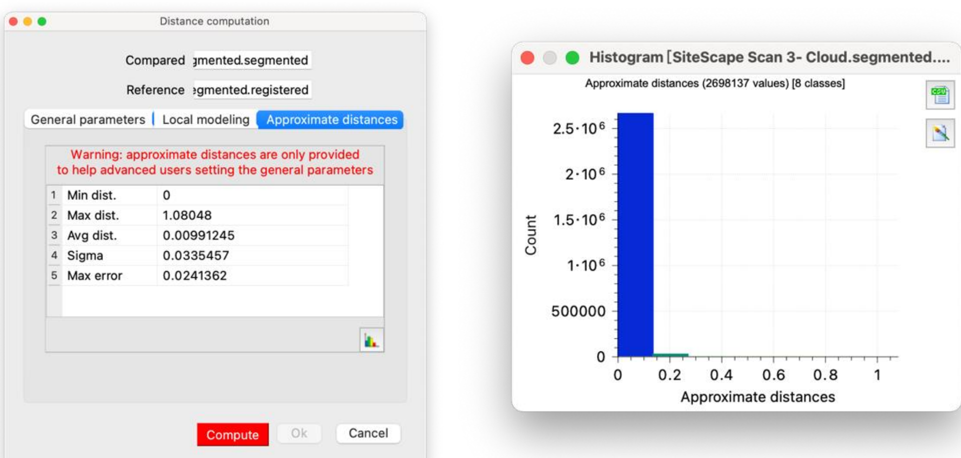


Figure 4-82, Approximate distance and Histogram for *scan 3* and *scan 4*.

e) Click Complete then the Cloud to Cloud distance will be computed.

f) In the Properties window, change saturation to further analysis the range and portion of distant points.

The distance computation window provided an approximate distance between the two scans, and the histogram provided a graphical exhibition of the range of distance with a maximum distance of 1.080 meters and an average distance of 0.009 meters.

After the computation was completed, Figure 4-83 would be available from CloudCompare visualizing cloud-to-cloud distance between *Scan 3* and *Scan 4*. Since *Scan 4* was the reference, it was shown in RGB color; *Scan 3* as the compared scan was shown in the scalar field. Select the Scan 3 (compared scan) from DB Tree window and scrolled down the Properties window, a Scalar Field (SF) displayed parameters could be seen and adjusted.

The default setting after distance computation has a saturation ranging from 0.00003713 meters to 1.08476901 meters (Figure 4-84). White dots can be moved around to change the color range of saturation. Displayed option determines the range of saturation, points with a distance bigger than the setpoint displayed will turn grey. Saturation helps visually describe the distance between two clouds. The difference in color exhibit point distance in corresponding point clouds.

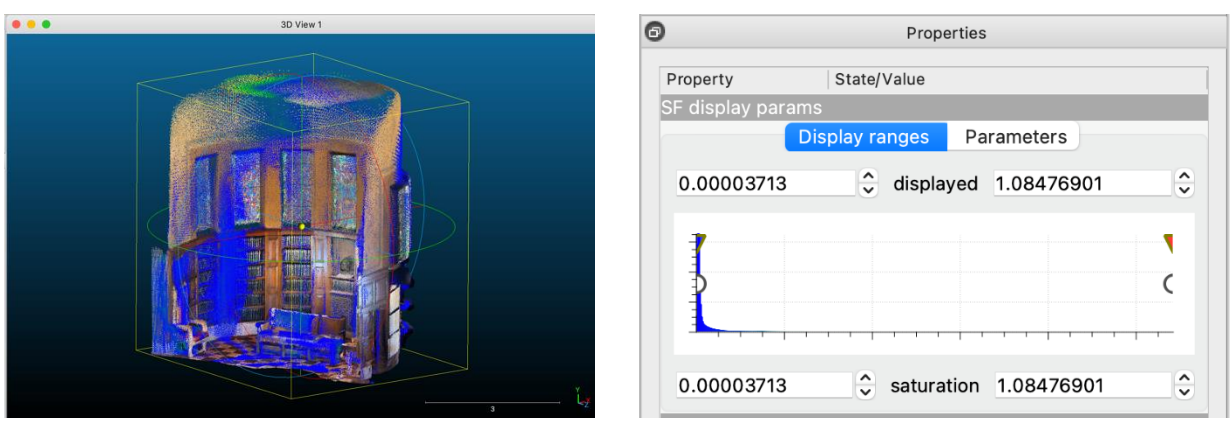


Figure 4-83, Cloud-to-cloud distance visualization from CloudCompare for *scan 3* and *scan 4*.

Figure 4-84, Saturation display range.

Adjust the saturation to 0.0254 meters (1 inch) and kept displayed at 1.08 meters; the Cloud to cloud distance and saturation display range changes (Figure 4-85). Changes in saturation helped represent the distance between clouds. Red over green over blue represented the distance from large to small. With a saturation setpoint of 0.0254 meters, red and green can be observed on corners, decorative panels, ceiling, and furniture, which represented a deviation of these areas on *Scan 3* compared to *Scan 4*.

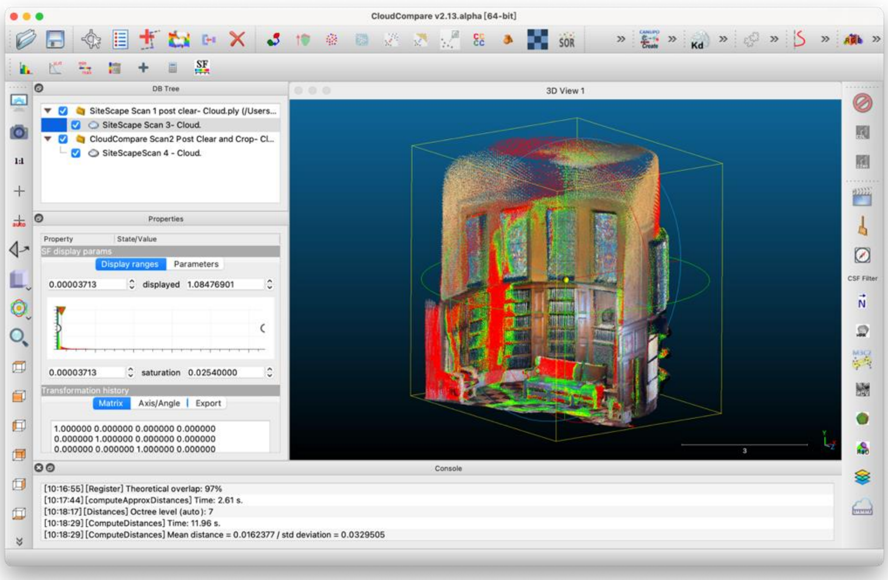


Figure 4-85: Scan 3 and Scan 4 distance with saturation 1 inch. Distance reduced from red to green to blue.

The results showed that there were areas such as bookshelves, statues, floors, and major building structures of both scans overlapping each other with a distance of less than 1 inch. However, ceilings, sofa, chair, and some floor areas were deviated larger than 1 inch, representing in red.

While with the current methodology, the scans still might not be useful solutions for heritage preservation users, who want to monitor the changes of building overtime, because the researcher was unable to validate the repeatability of scans and captured points. However, the result does not negate the potential of the methodology because the following possible impacting factors cannot be ruled out 1) the data acquisition path for both scans were not exact same. Different scanning routes may cause the deviation, 2) scan alignment did not exact overlap the two scans, 3) the distance computation in CloudCompare only measured nearest neighbour distance, but not the true distance (Figure 4-86). Thus, the methodology for monitoring heritage conservation purposes is not recommended until further research been done in the control of scanning path, the validation of alignment computation, and the measurement of the true distance between two point clouds. The results only exhibit a preliminary assessment to smartphone acquired data, further comparison will be made in Chapter 5.

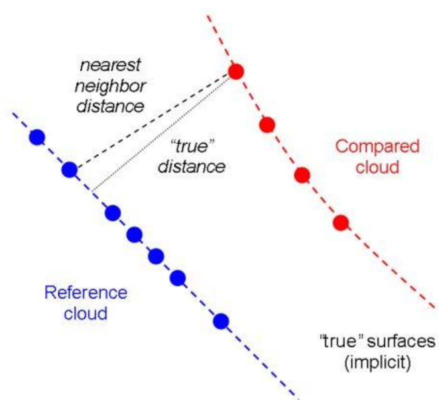


Figure 4-86: CloudCompare distance computation working principle

4.4 Smartphone scanning overview and directions for Education

Matterport Capture smartphone application was used in creating virtual tour for heritage conservation education exhibition purposes. A data acquisition and data process instruction will be given. A tripod is recommended for following the start-up guide.

4.4.1 Data acquisition

Data acquisition was completed with the Matterport Capture app on the smartphone device with a tripod. Different from the SiteScape app which allows free movement during capture, Matterport Capture required the device to be stable in one place. A tripod was used helping fixed the device at the same time able to turn in spherical degrees.

I. Preparation

To generate a virtual tour through smartphone, Matterport Capture should be downloaded, registered, and set up.

a) Have smartphone application Matterport Capture download to the device, and smartphone stabled on a tripod.

b) Open Matterport Capture and sign up a free account (Figure 4-97, 4-98).

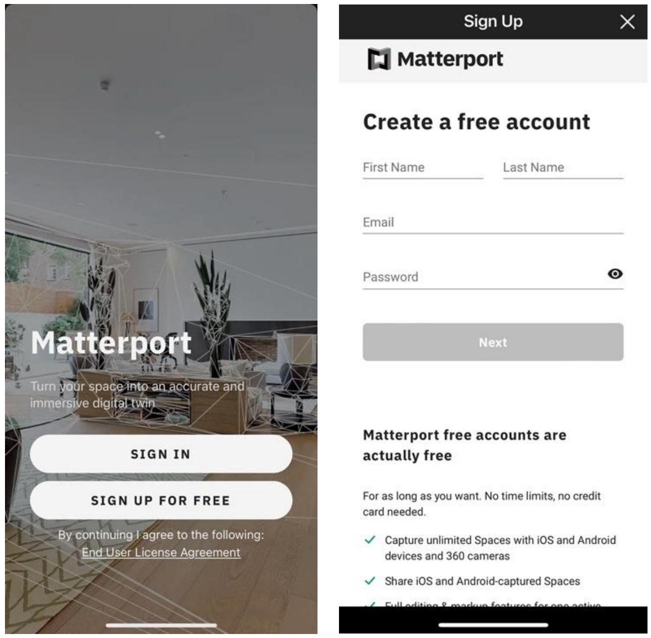


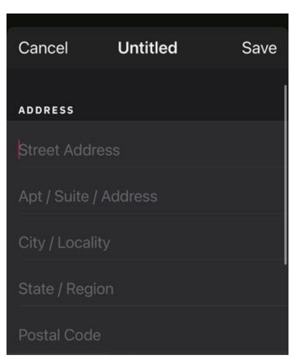
Figure 4-87 and 4-88: Matterport Capture register interface

c) Remove unwanted furniture or objects from the physical space.

II. Data Acquisition

Spatial information can be acquired through Matterport Capture and therefore create a virtual tour.

a) Go to My Jobs, click on + New Job. Fill in address information (Figure 4-89).



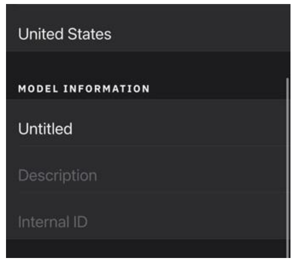
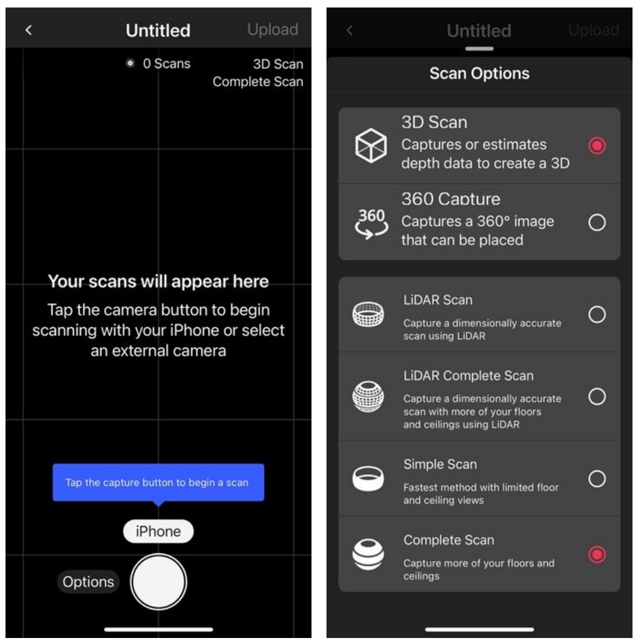


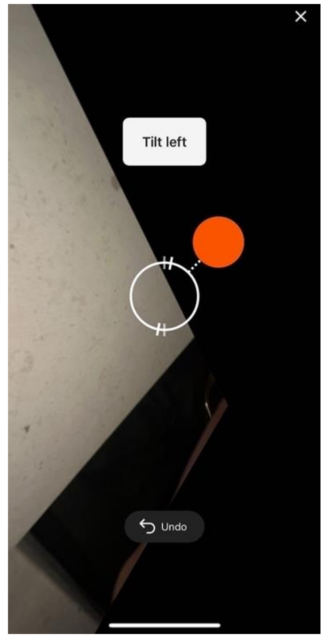
Figure 4-89: New job address information

b) Click Option, select 3D Scan and Complete Scan (Figures 4-90, 4-91).



Figures 4-90 and 4-91: Scan interface and parameter selection

c) Follow the instructions on the screen to point the camera at the dots, move to next one until finished (Figures 4-102, 4-103)



Figures 4-92 and 4-93: Scan process

d) Take at least three to four 360 degree photos in one space, more when documenting narrow space and doorways.

e) After a scan is finished, trim and add window to the model on the smartphone app (Figure 4-94).

Figure 4-94: Trim and add window interface

f) Upload to cloud one at a time.

g) For each room, include at least three captures from different standing points. Ensure overlap area between two scans, which enhance the automatic registration.

4.4.2 Data processing

Matterport captured 360 photographs can be uploaded, edited, and shared publicly.

I. Data Editing

Data editing can be done with Matterport project website, which includes various built-in functions such as measurements and different views.

a) Go to Matterport webpage: https://matterport.com. Click on Get Started Free, log in Matterport Capture account (Figures 4-95, 4-96).

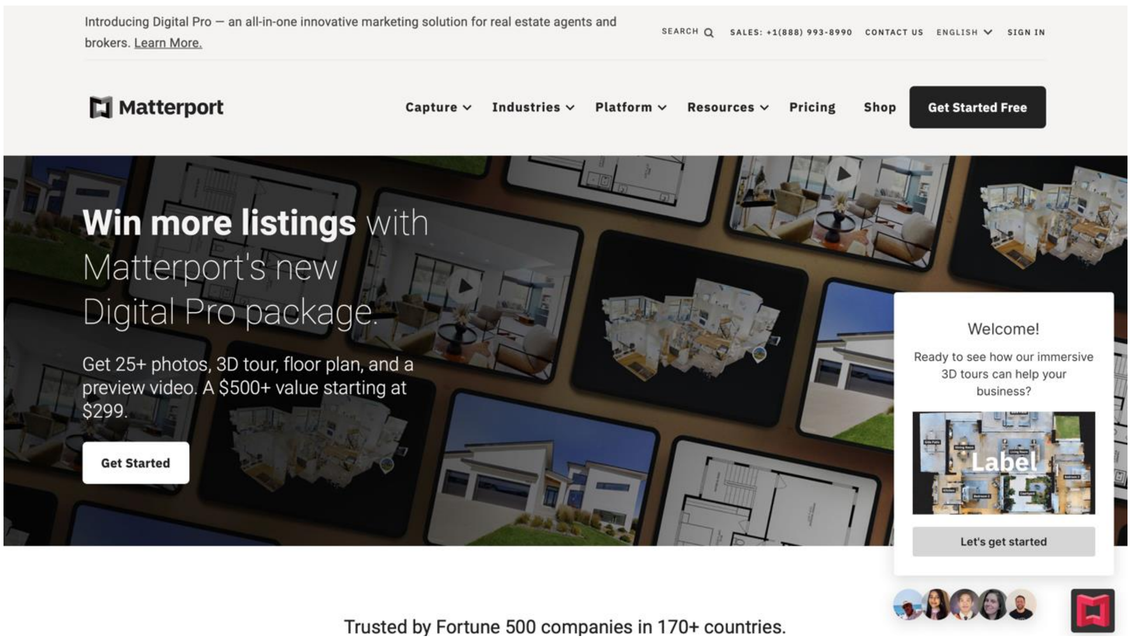


Figure 4-95: Matterport webpage

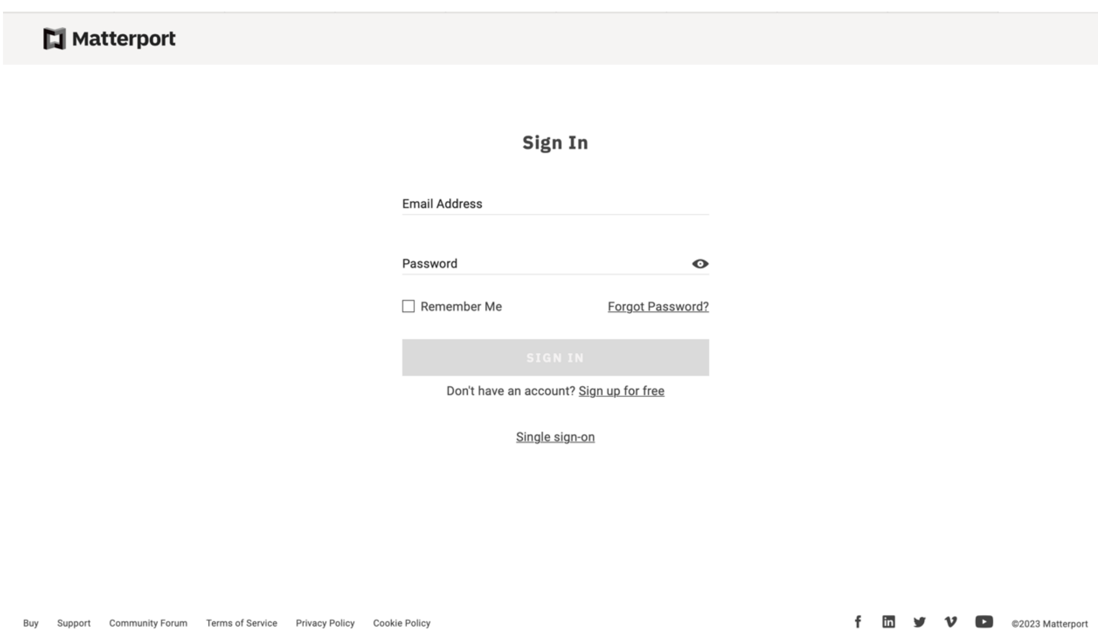
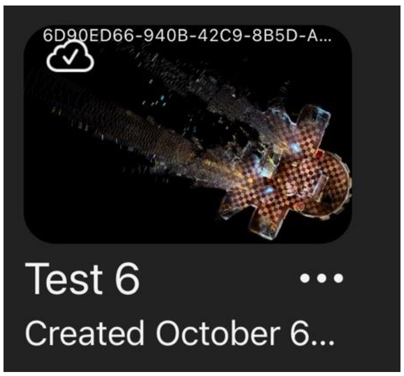
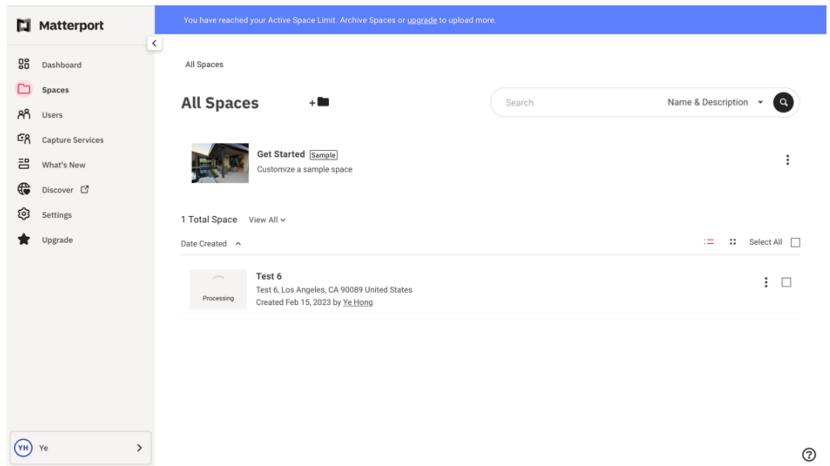


Figure 4-96: Matterport sign in

b) Once the project shows uploaded, users can view their projects on the website (Figures 4-97, 4-98).





Figures 4-97 and 4-98: Matterport project uploaded, and Matterport Space

c) Open the project on the web page; click on start button to explore the building in virtual space (Figure 4-99）.

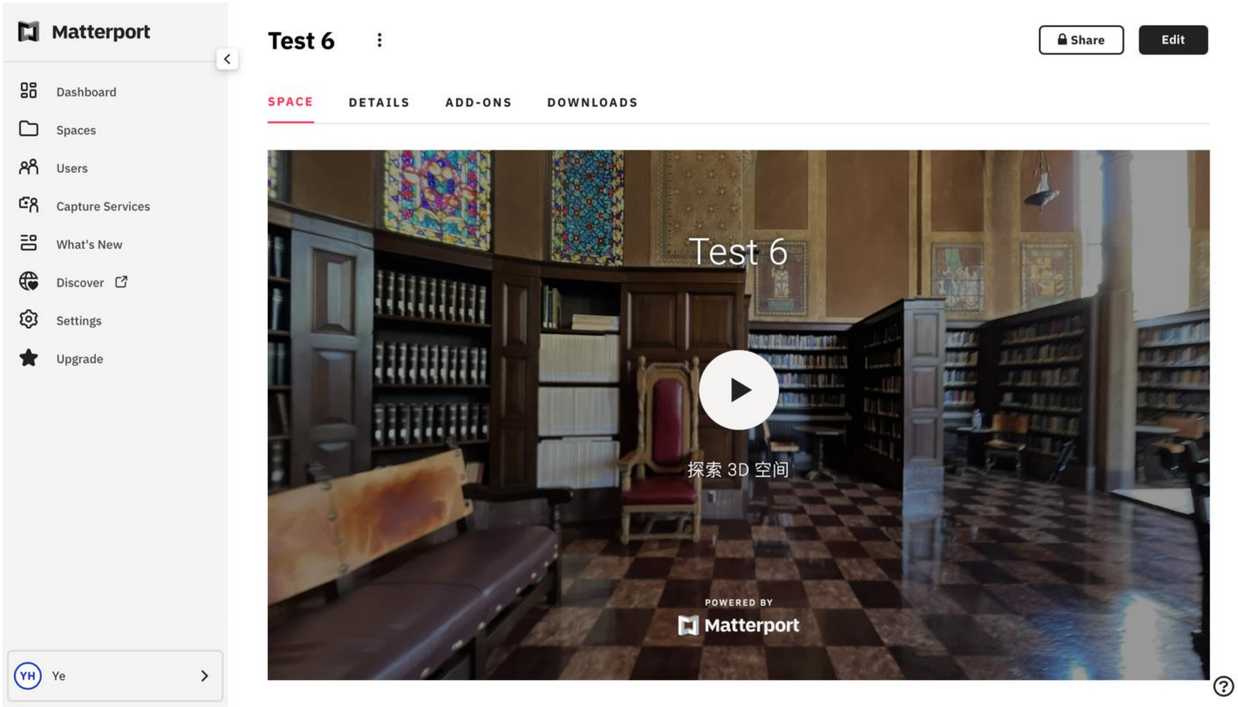
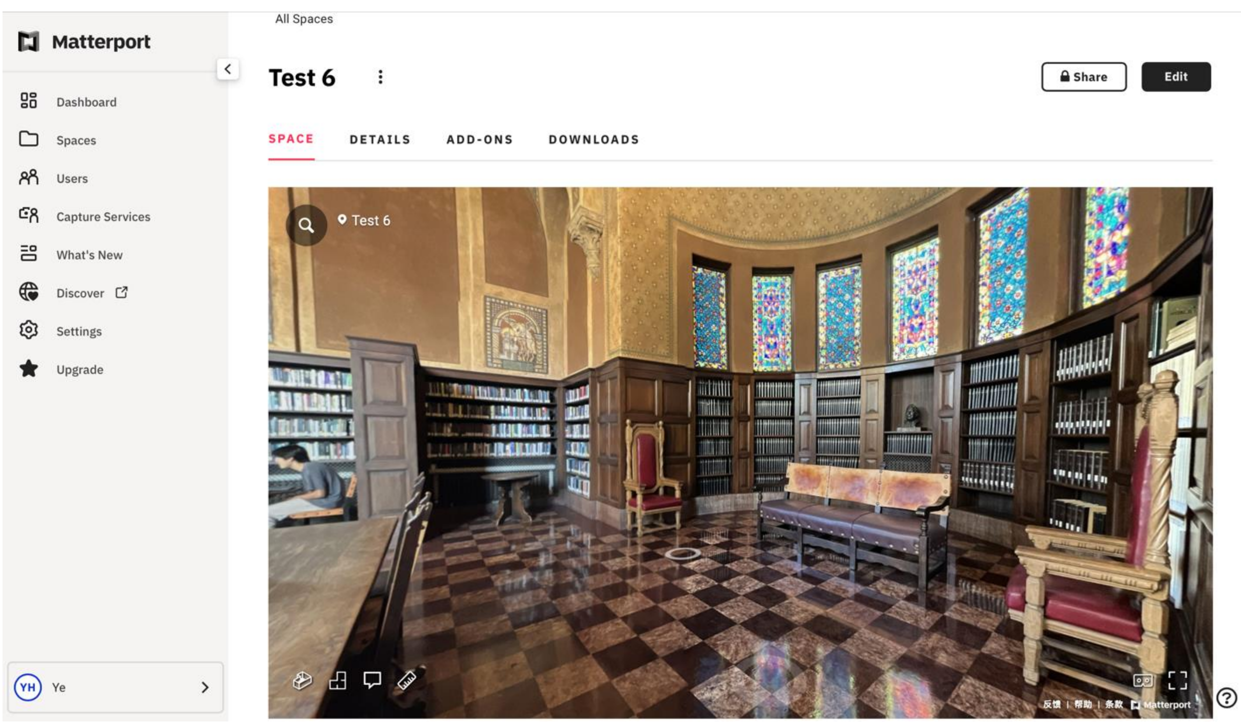
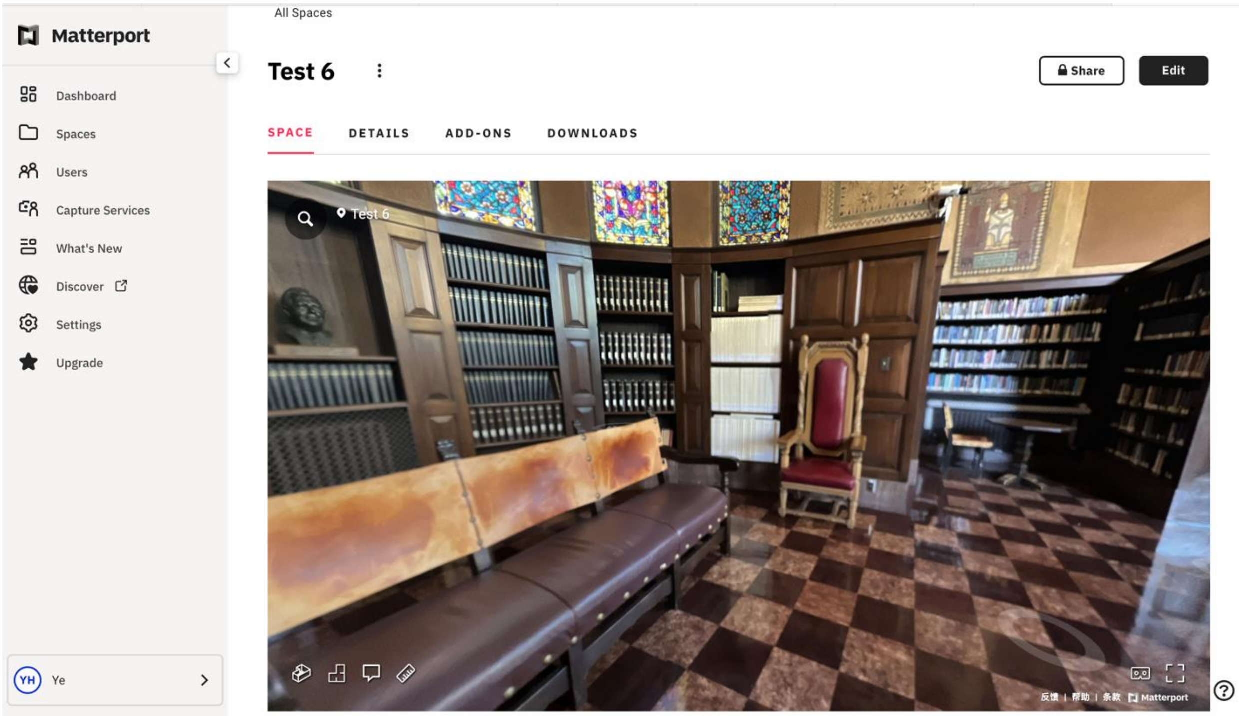


Figure 4-99: Matterport project space

d) Move around by clicking on white circles in view to check different views (Figures 4-100, 4-101).



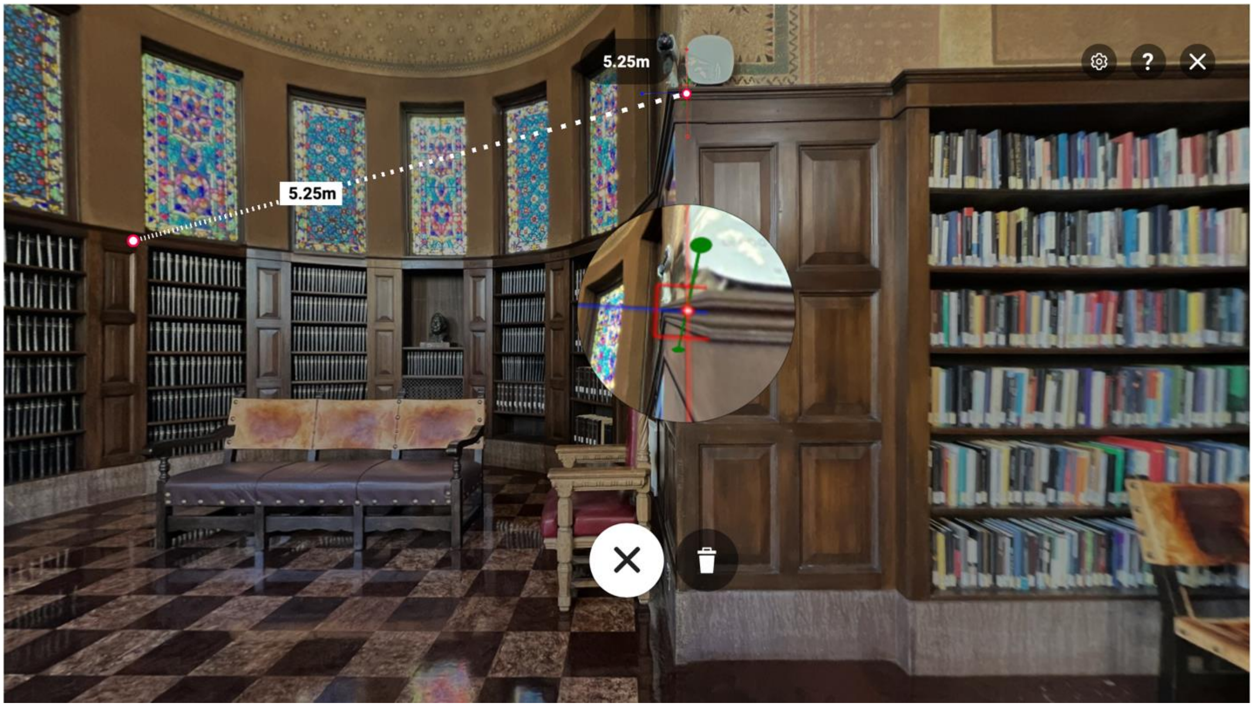


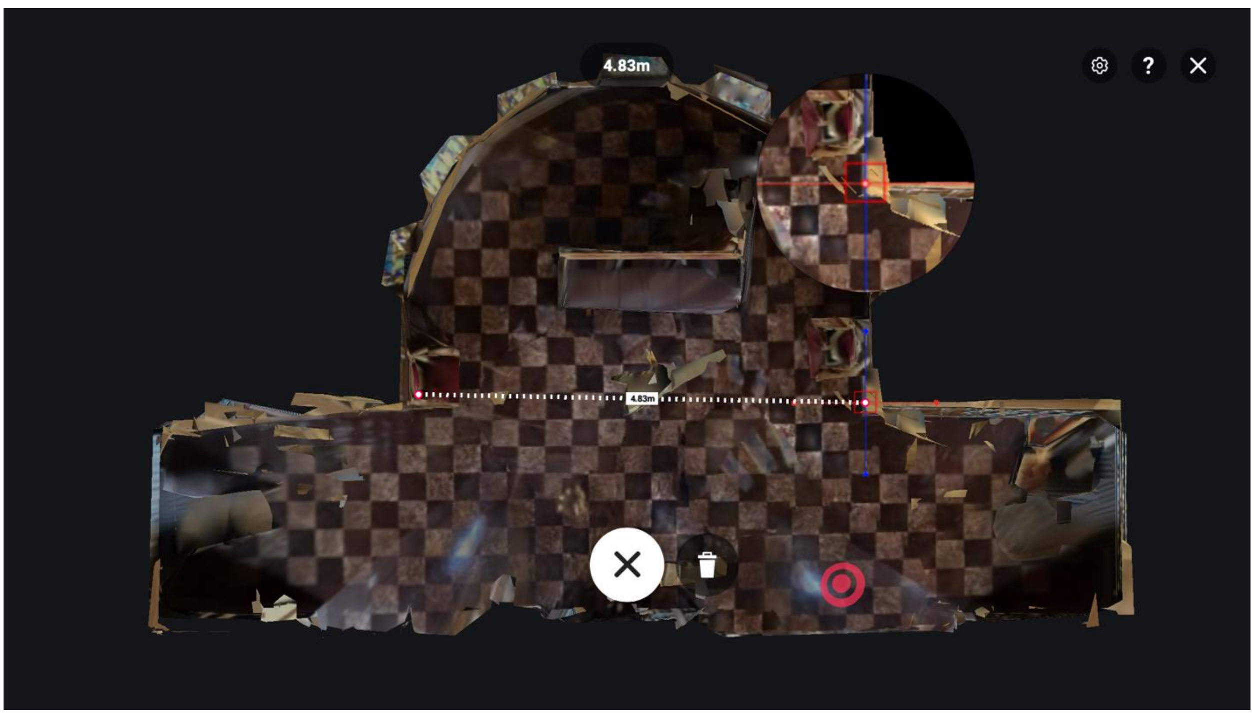
Figures 4-100 and 4-101: white circles and different views of a project

e) Matterport enables a doll house view, floorplan, and measurements (Figures 4-102, 4-103, 4-104, 4-105)

Figure 4-102: Doll house view

Figure 4-103: Floorplan view





Figures 4-104 and 4-105: Measurements can be taken from any view mode

II. Sharing

To create an accessible virtual tour and share, researcher should adjust details and privacy settings on Matterport project webpage.

a) Click on Details, adjust information (Figure 4-106)

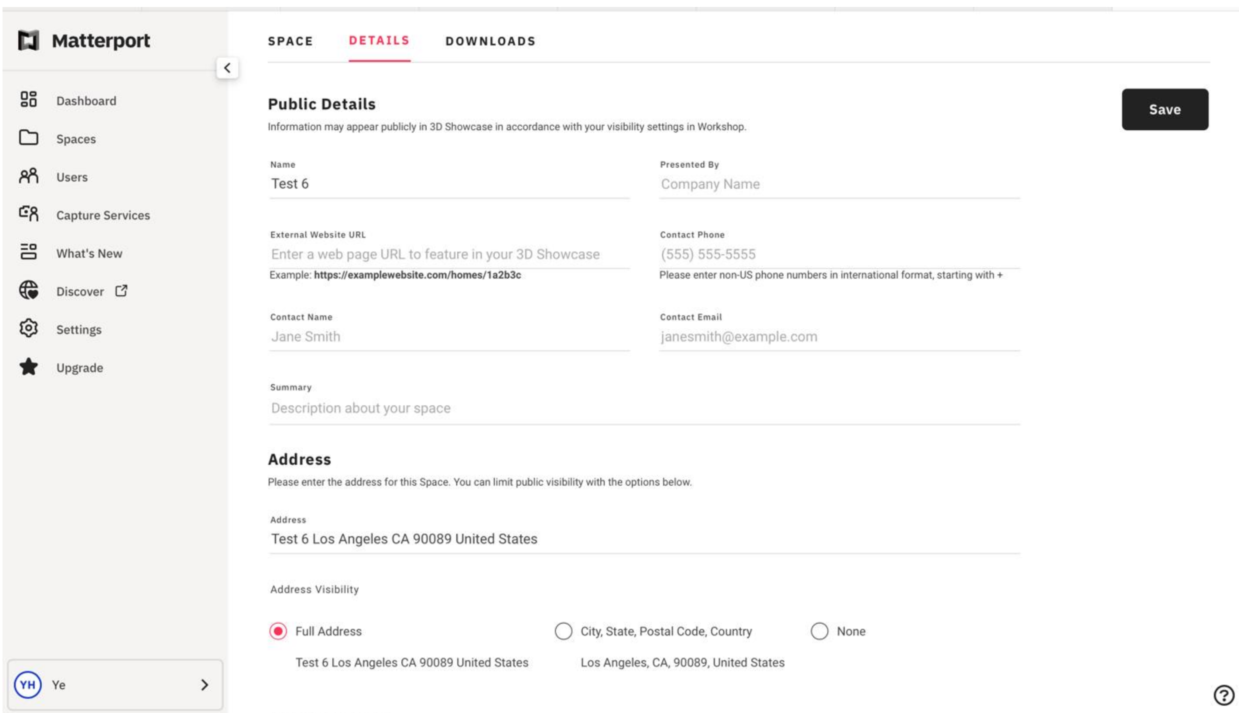


Figure 4-106: Matterport project details

b) Additional services such as export to an E57 file (If data is scanned with LiDAR mode, it can be exported as an E57 file as point clouds), a BIM file, and schematic plan can be all be ordered from Matterport for a charge (Figure 4-107). Various add-ons offered by Matterport allow users to further extract information from the scan for usages in different fields.

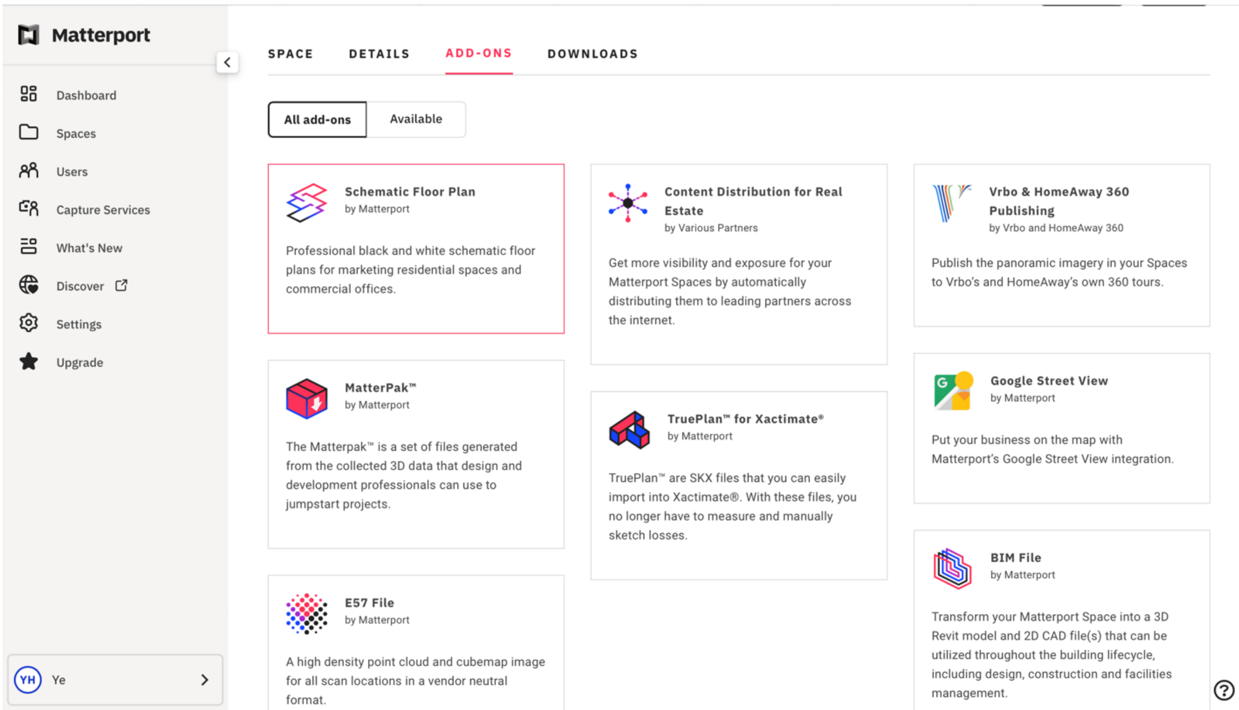


Figure 4-107: Matterport add on features

c) Click on Share and select private for personal use, password protected for personal share or public for general public. Users can select level of detail and information they want to share through options (Figure 4-108).

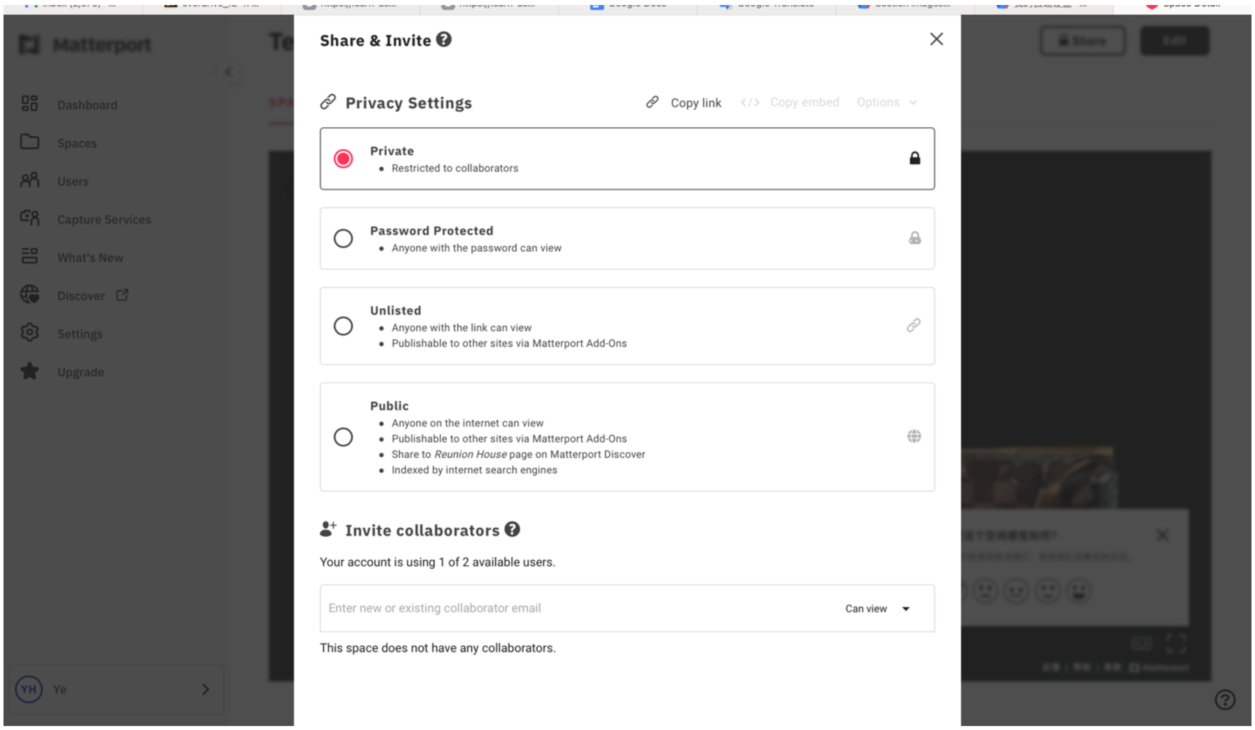


Figure 4-108: Share and Invite page

d) Copy link to share or insert into individual project websites. Matterport can also be embedded in users' own website through using embed code, for more detailed instruction see https://answers.pagecloud.com/help/matterport and https://support.matterport.com/s/article/Embed-a-Matterport-3D-Model?language=en_US. Anyone with a shared, public accessed link and internet can view the virtual tour. If the virtual tour is embedded in a website, it can be view from the webpage.

4.5 Summary

Chapter 4 is mainly a user guidance for users interested in gathering 3d point cloud data. It gave detailed instruction on how to scan and use the scanned data for different purposes.

- 4.1 introduced the process taking multiple scans of an interior with SiteScape and merging them together to generate floor plan. The test scan exhibits the possibility of creating the product of a floorplan, which will be conducted again in the case study and compared with data acquired from a professional scanner.

- 4.2 described scanning the same area with point density parameter in low, medium, and high with SiteScape. Two of the three scans were processed and used for comparing the possibility of overlaying scans to increase accuracy. The validity of this methodology will be examined in case study through comparing with scanner's data as ground truth in Chapter 5.

- 4.3 introduced the process of acquiring geometric data of the same area with same parameter in SiteScape. CloudCompare was used to compute the distance between the two exact scans (*scan 3* and *scan 4*) to examine the repeatability of smartphone scanned data. 4.4 used Matterport Capture for iPhone and a tripod to take 360 degree photographs and generate a virtual tour. The file was uploaded to website and can be shared through links.

- 4.4 described how to use create a smartphone 3d virtual tour with Matterport Capture that can be shared through links on a website.

The results from test scans show that all four methodologies are relatively straightforward. For site survey purposes, a floor plan was created. Further comparison between the floor plan to scanner scanned data will help in examine the hypothesis. Using smartphone 3d scan to document cultural heritage was shown; the result shows overlapping two scans can increase the points describing the same surface,; however, a thicker layer of point may not contribute to documentation because of increased error. In test scans for monitoring purposes, two scans with the same parameter and a scan path was used to computed the cloud to cloud distance. The distance exhibited that smartphone scanned data cannot produce repetitive data every time unless with more stable scanning methods or better alignment computation. Issues found in current methodology for documentation and monitoring will be discussed further in Chapter 5 Case Study

Chapter 5 Case Study Smartphone Scan Result

Chapter 5 discusses the results of 3d scanning from an iPhone and a professional scanner and a laser measure at the case study Reunion House. The Reunion House is located at Silverlake, California. The project was built in 1951, designed by Richard and Dion Neutra. The case study takes the master bedroom as an example, scanned by both smartphone and professional scanner device (Figure 5-1). Christopher Gray, Associate Reality Capture at GB Geotechnics USA Inc (GBG), introduced Alan D. White to conduct the professional scan. White is a technician of AQYER, a company specializing in non-destructive evaluation and as-built documentation, has made a significant contribution to the research project. He conducted a professional scan for the sake of Neutra Reunion House: Documentation Workshop lead by Western Chapter of the Association of Preservation Technology International and generously shared the scan data (WCAPT, 2023). The professional scanner used is a Leica RTC 360 scanner, which is commonly used for small and medium project. White's data has enabled the comparison between the iPhone scan and professional scanner scan. His commitment to the preservation of the Neutra Reunion House is unparalleled, and his contribution to the project is highly appreciated.

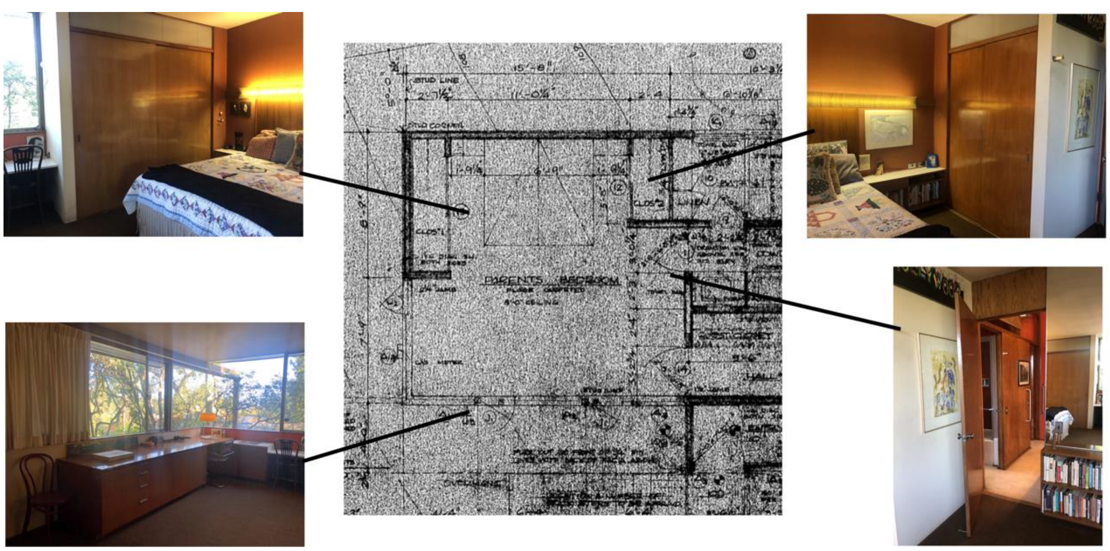


Figure 5-1: Master bedroom in Reunion House

The measurement results from smartphone scans, professional scanner scans, and laser distance measurements data will be summarized. Smartphone scanned results will be compared to the other three methods. Scans acquired from smartphone and professional scanners will be imported to AutoCAD. Dimensions of all three methods will be compared and a range of error will be calculated. The comparison results will be summarized in a table. Recommendations will also be made based on the comparison results. The results will help to guide the selection of the most appropriate method for a specific application in Chapter 6.

5.1 Evaluation standard

When generating drawings and models for heritage conservation, it is important to ensure that the scale and standard of accuracy are appropriate. The smartphone scan was evaluated based on HABS requirements, which accepts paper files. Recording Historic Structures introduced the scales used for architectural drawing (Table 5-1) (Burns, 2004). Different from digital drawings, drawing on paper scale is related to the size of paper. With fixed size of board and paper, scale and line weights can impact accuracy. The most common architectural scale is 1/4” = 1’-0”, with the smallest unit of 1” (Burns, 2004). Such scale includes reasonable amount of detail possible. To document windows and doors, and other features of similar scale, 3/4”= 1’-0” scale with a smallest unit of 3/8” are mostly used. To test the ability of smartphone scanned data in assisting as-built drawings on paper, scale 1/4” = 1’-0” and 3/4” = 1’-0” would be used in evaluating the performance of scanned data. To identify the smallest unit for scale 1/4”=1’-0” and 3/4”=1’-0”, accuracy/ precision should reach or smaller than a factor of two than the smallest feature, thus 1/2” or 3/16” (Burns, 2004). Digital documentation always require a 1/8” of accuracy for tracing room size three dimensional models, floor plan, or section drawings (White and Gray, 2022). To create engineering drawing and maps, the most common scale is 1”=20’ with a smallest unit 0.4’ (Burns, 2004). In order to determine 0.4’ in a map, a factor of two than the smallest feature, which is 0.2’ (2 2/5”) is needed.

When evaluating smartphone scans, the smallest units of 1/2” or 3/16”, 1/8”, and 0.2’ (2 2/5”) will be used as a standard (marked in red).

Table 5-1: Architectural Scales for drawing (Burns, 2004)

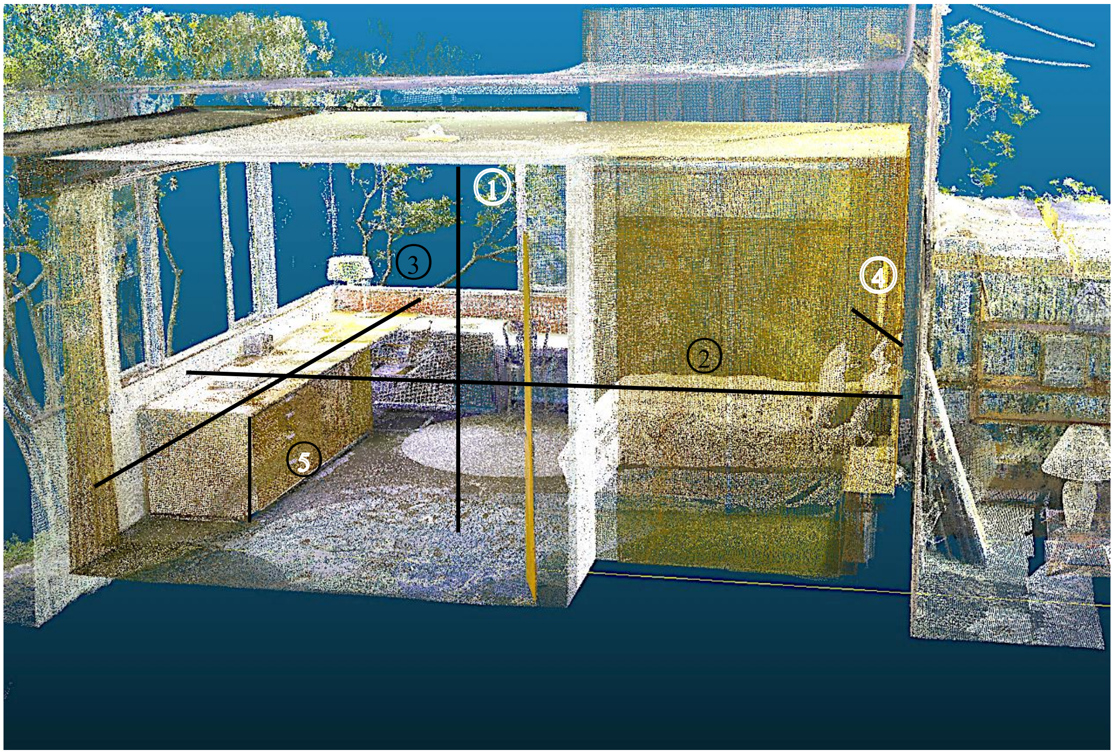
Scale	Smallest Unit	Evaluating Unit	Use
1/16" = 1'-0"	4"	2"	Drawings of large structures without details.Materials shown in plan only.
1/8"=1'-0"	2"	1"	Little detail possible. Materials shown in plan, only large units in elevation.
1/4"=1'-0"	1"	1/2"	The most common architectural scale. Reasonable amount of detail possible. HABS/HAER shows door and window frames, materials in both plan and elevation. At this scale, line weights can adversely affect accuracy. A 3x0 (0.25 mm) line is approximately 1/2" thick.
3/4"=1'-0"	3/8"	3/16"	Most common scale for door/window elevations and other features of similar scale.
1 1/2"=1'-0"	3/16"	3/32"	Details of door/window jambs/frames, large tools, small machines, etc.
3"=1'-0"	3/32"	3/64"	Details of objects such as hardware, tools, etc. and molding profiles.
Full Size			Small or intricate objects, elaborate moldings and ornamentation

Table 5-2: Engineering and map scales (Burns, 2004)

Scale	Smallest Unit	Evaluating Unit	Use
1"=5,280'	104'	52'	USGS 15 minute map
1"=2,000'	40'	20'	USGS 7.5 minute map
1"=40'	0.8'	0.4'	Site map
1"=20'	0.4'	0.2'	Very common scale for residential-size site plans (at this scale a half-acre lot fits comfortably on a legal-size page in a deed book). Distances given in feet and hundredths.
1"=16.66'	0.33'	0.165'	Site map
1"=10'	0.2'	0.1'	Small site map
1"=8.33"	0.166'	0.083'	small site map

5.2 Scanned data results

Scans were exported as point clouds in E57 file. After being processed in Autodesk Recap, the file was saved in rcp. format then imported to AutoCAD. In AutoCAD, RTC 360 scan was set as the ground truth; the iPhone scanned point clouds would be aligned to it. Then, measurements were documented and compared. To control impact factors, six targets are set in the comparison: 1) master bedroom height 2) master bedroom width 3) master bedroom length, 4) master bedroom closet to closet distance 5) desk height, and 6) point clouds thickness (Figure 5-2). The six measurements were documented and listed in tables for comparison.



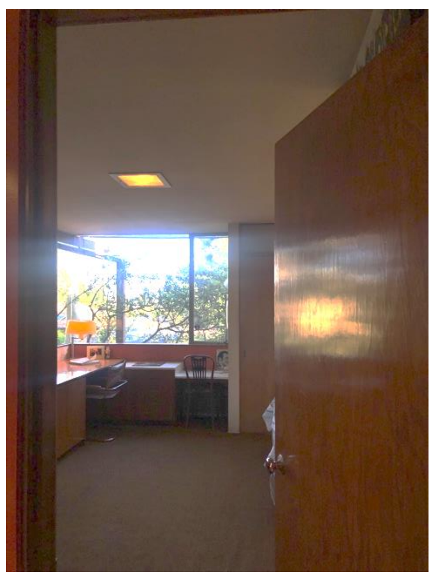


Figure 5-2: Reunion House master bedroom and six targets

Seven smartphone scanned point clouds were selected for the comparison, including

1) a raw low point density scan on tripod,
2) a raw high point density scan,

3) a merged high point density scan,

4) a raw low point density scan,

5) a merged low point density scan,

6) a raw floor to ceiling scan, and

7) a merged floor plan from multiple scans.

Smartphone scanned data acquired on tripod was compared to scanner scanned data. Professional scanner laser sensor rotated 360 degree in horizontal and vertical axis except for a small area where the tripod stood (Figures 5-3 and 5-4). Smartphone device was stabled on tripod; during a scan, smartphone only rotate on vertical axis (Figures 5-5, and 5-6). Limited by the angle of smartphone LiDAR sensor, ceiling and floor had two circles of blank area. Impacted by the angle of laser shooting on surface, ceiling and floor are barely captured. Tilting smartphone up and scan can create less blind area on ceiling; tilting smartphone down can create less blind area on floor (Figures 5-7, 5-8, 5-9, and 5-10). A more complete scan can be merged with two angled scan (up and down) and a leveled scan. (Figure 5-11).

Figures 5-3 and 5-4: Professional scanner scan and moving path

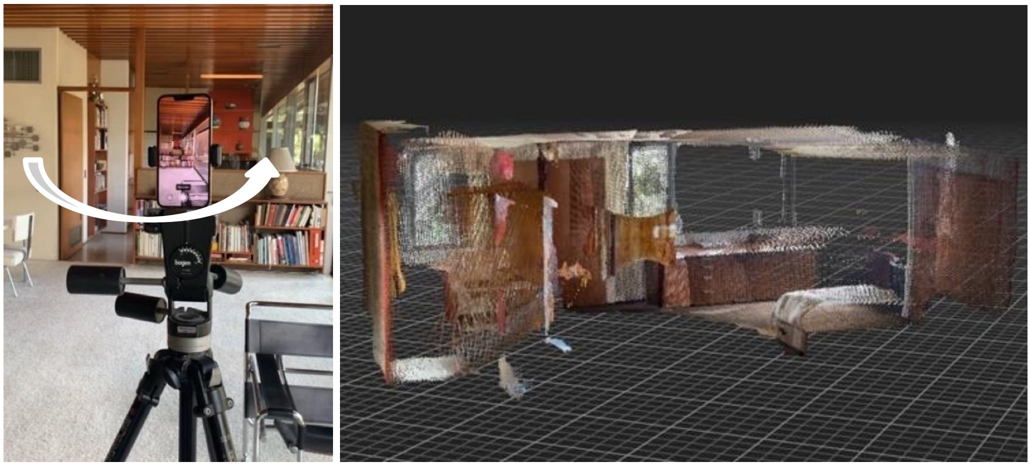
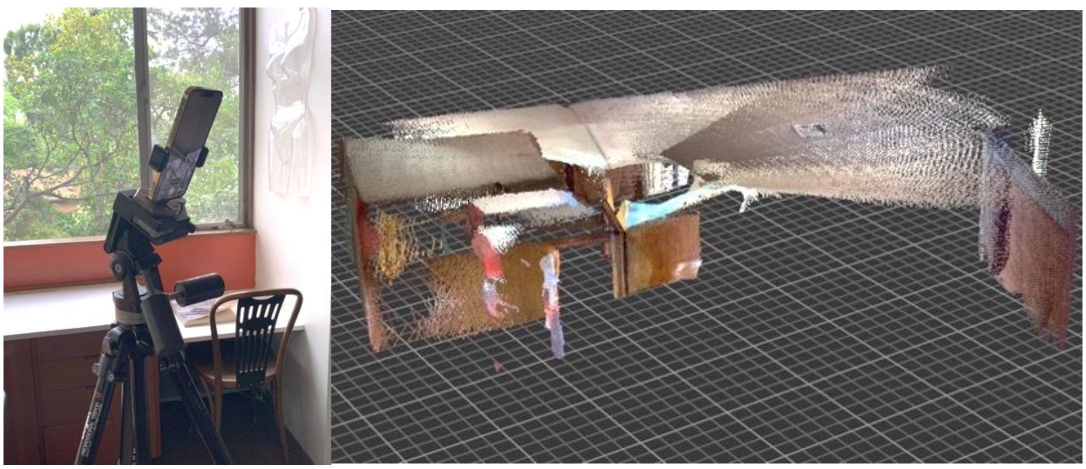
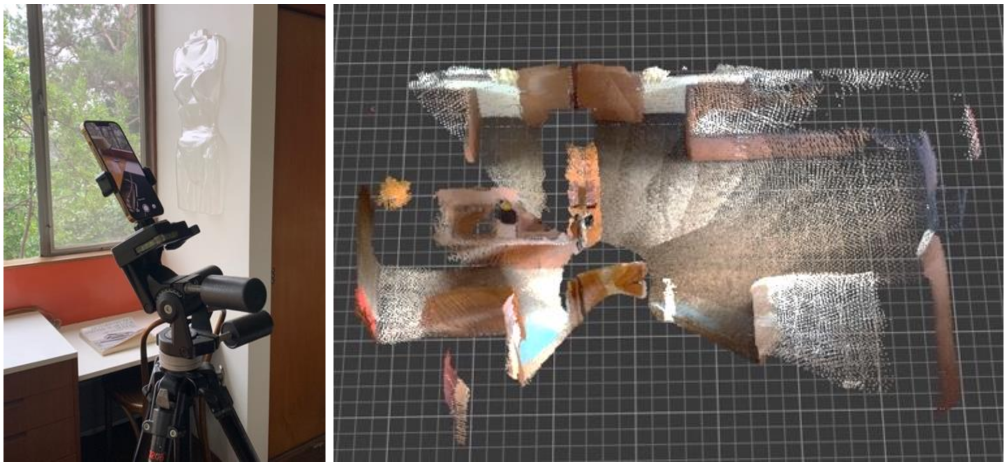


Figure 5-5 and 5-6: Smartphone scan moving path and scan result



Figures 5-7 and 5-8: Smartphone device tilted up and scan result



Figures 5-9 and 5-10: Smartphone device tilted down and scan result.

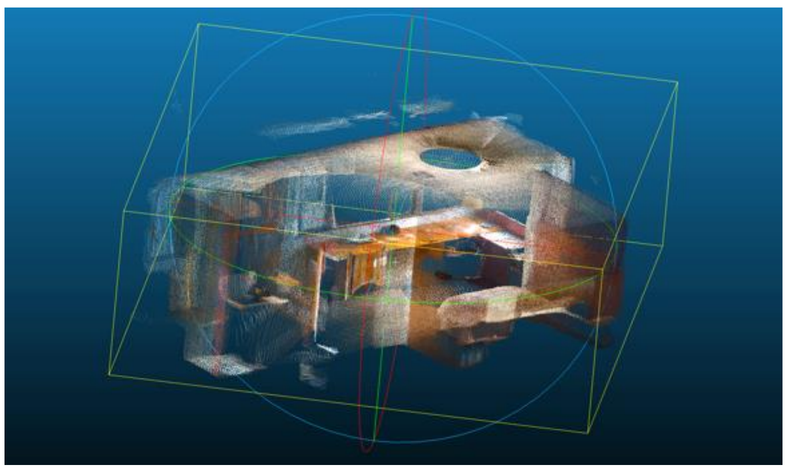


Figure 5-11: Three smartphone scans (leveled, upper and lower angled) merged with CloudCompare

Smartphone scans (red) were overlapped and aligned manually with professional scanner captured point clouds (green) (Figure 5-12). Three floor plan sections were created to observe the difference and measure the distance between smartphone scans to Leica RTC 360 scanned data in Autodesk (Figures 5-13, 5-14, 5-15, 5-16). The measurements were done through tracing the point cloud and using the linear dimension tool. Dimensions were documented in tables; error and error rate were calculated. Results were analyzed and compared to determine which scan yielded the most accurate measurements in 5.2.1.

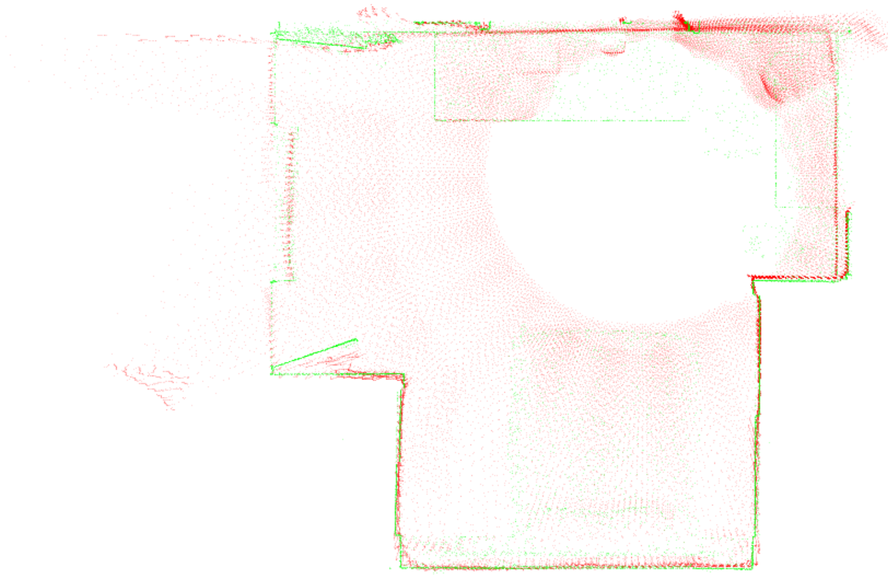


Figure 5-12: Manual align smartphone scans (red) with professional scans (green).

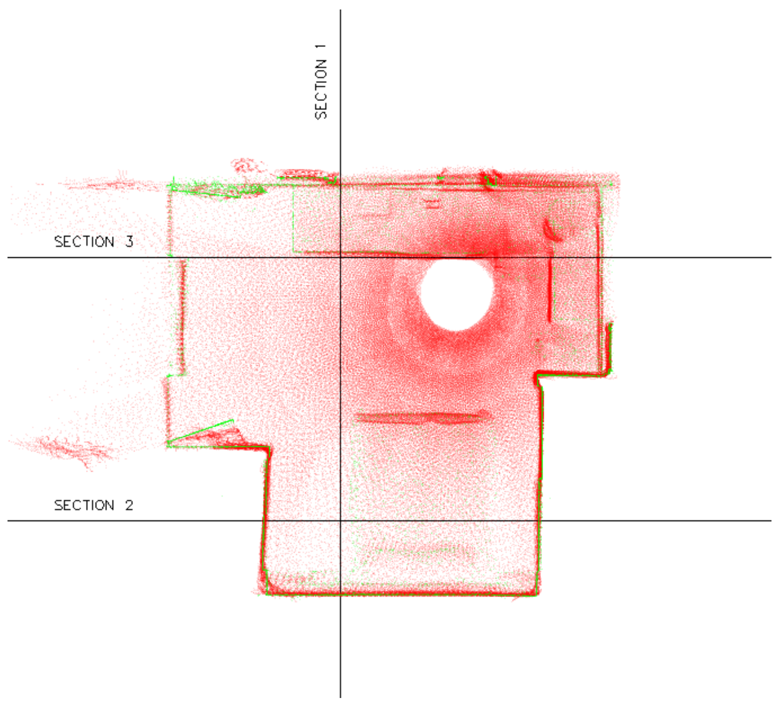


Figure 5-13: Section layout on point clouds

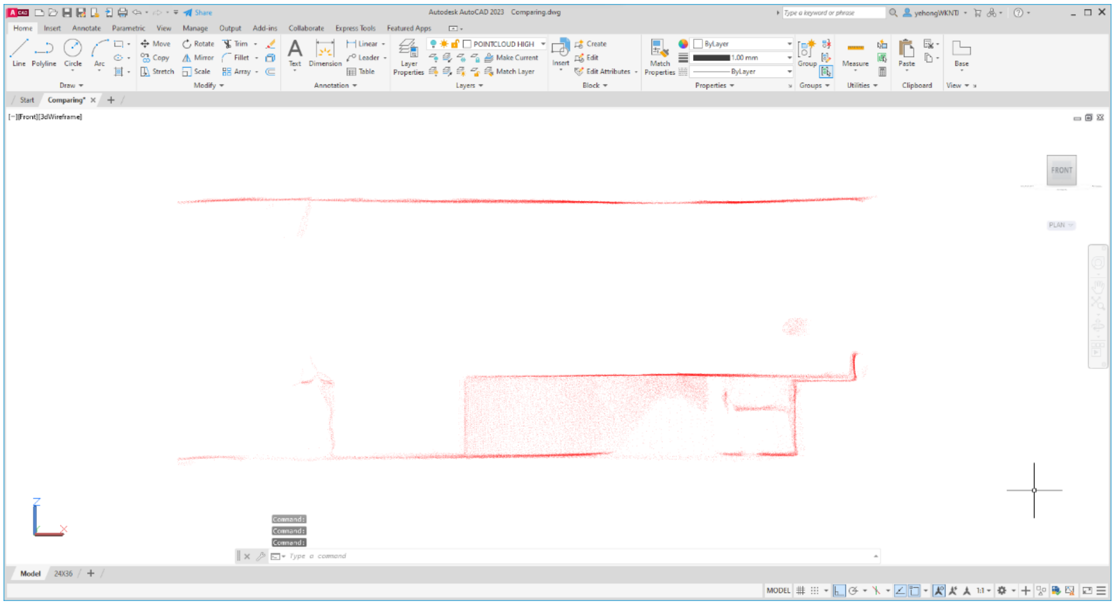


Figure 5-14: Section 1 in AutoCAD

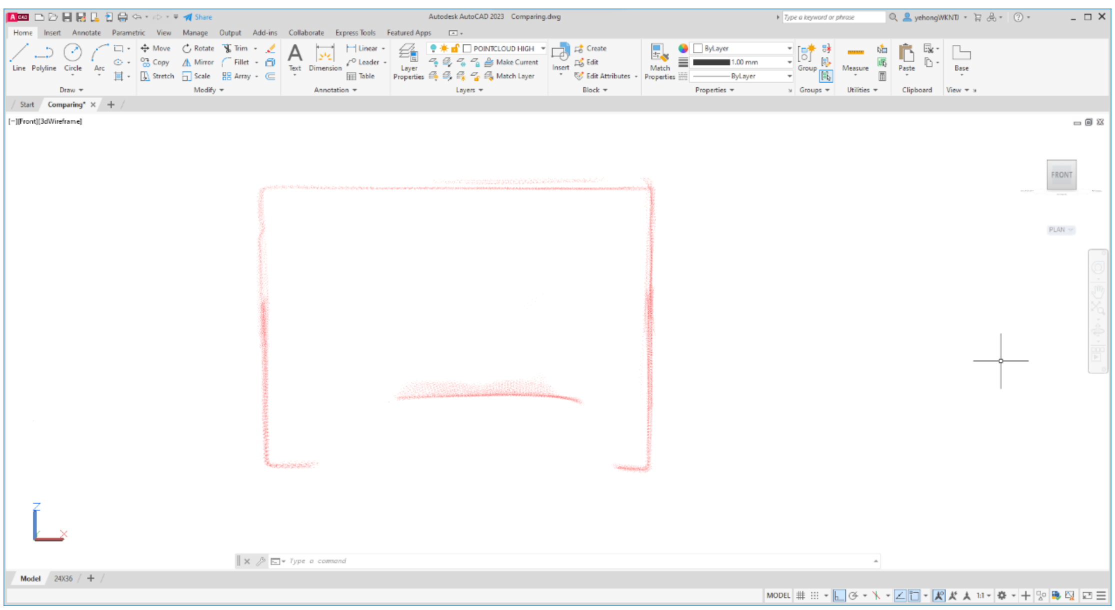


Figure 5-15: Section 2 in AutoCAD

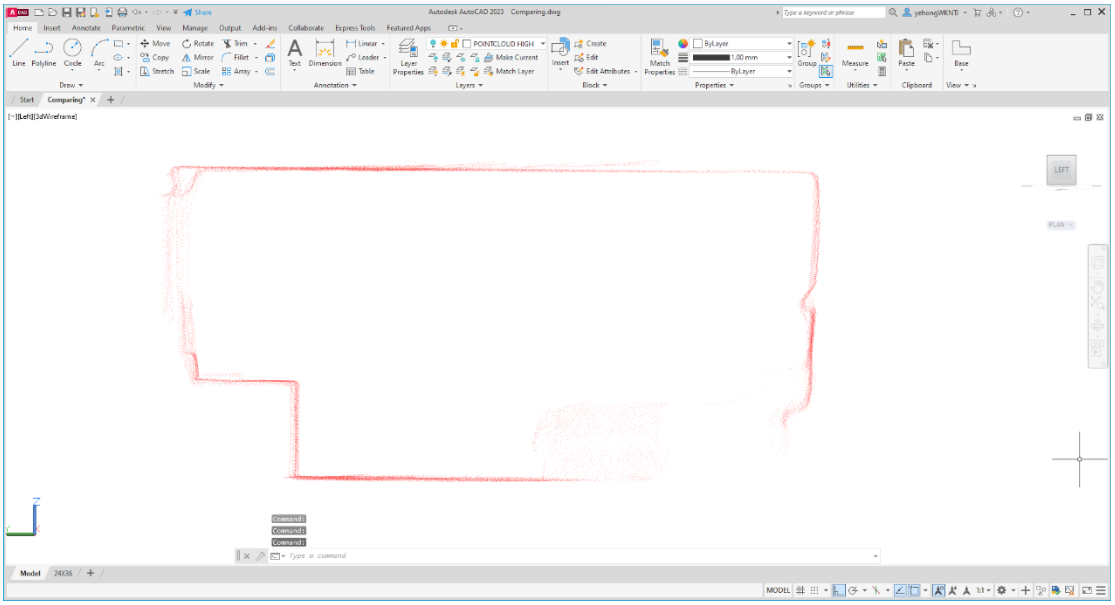


Figure 5-16: Section 3 in AutoCAD

A section drawing is a vertical cut through a structure or site, which provides vertical information and reveals the arrangement of objects and spaces. It shows a series of room elevations, separated by walls, floors, and ceilings, in relation to one another. Sections are similar to floor plans except they are cut perpendicular to the floor, and the visible surface beyond the cut line are room elevations instead of a floor. Tracing and measurements from a section can only include room height, as room length and width cannot be determined in the same section.

Room dimension is measured individually in all eight scans through the plans and sections. In each measurement, the section was first traced and then measured (Figure 5-17). Because laser only travels in straight line, scans can have blind areas. The blind areas in iPhone acquired scans that are not applicable for measurements are shown N/A in tables. One wall was missing in smartphone scanned data; thus the width of room cannot be measured (Figures 5-18 and 5-19).

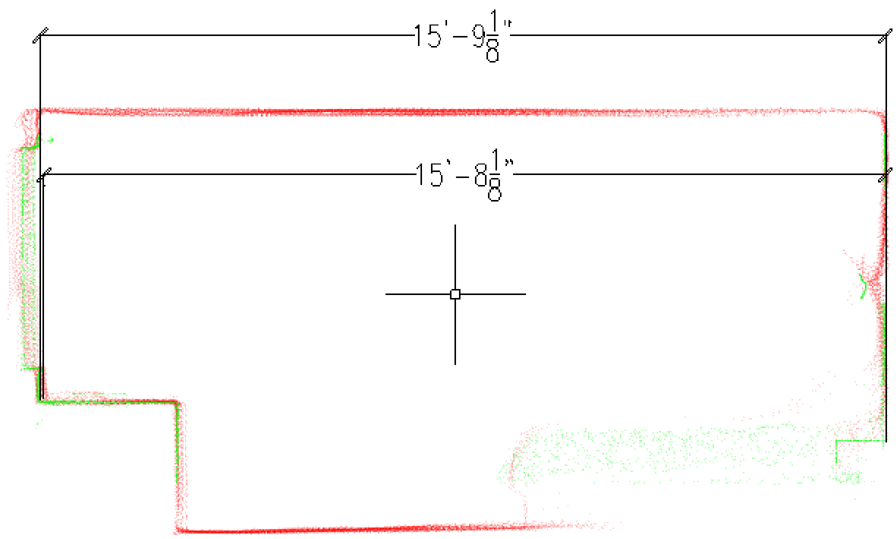
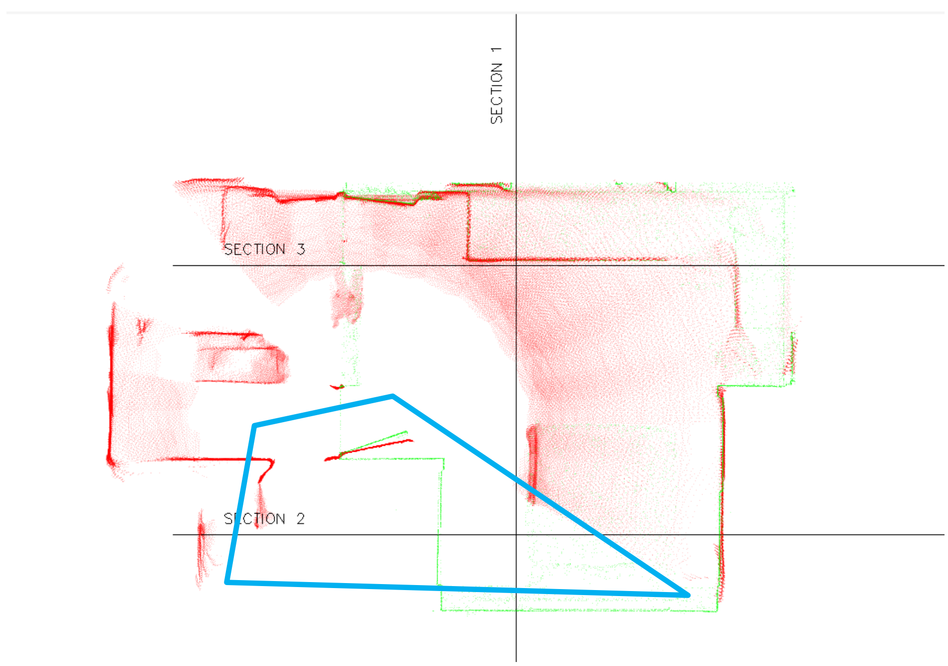
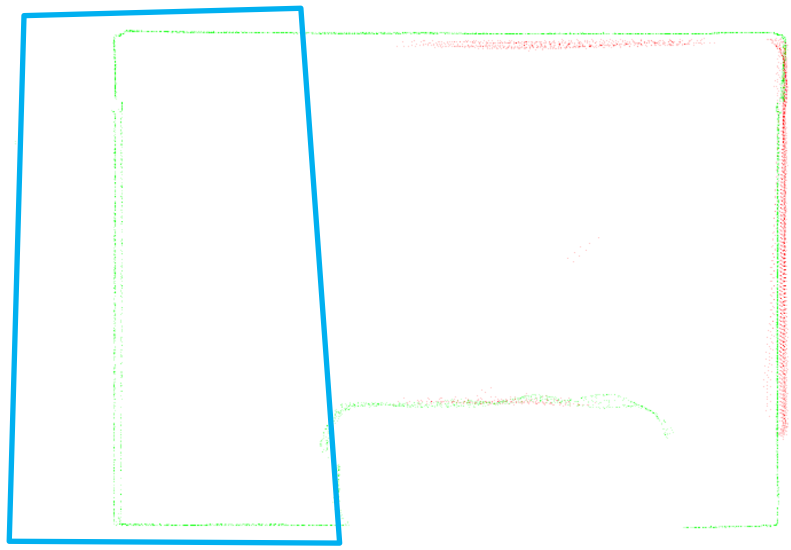


Figure 5-17: Measurement example (room width) of iPhone acquired low point density merge scan (red) and professional scan (green) in section 1





Figures 5-18 and 5-19: Blind area (outlined in blue) observed from overlapped floorplan and from section 2 (high point density scan by smartphone in red).

Tracing of point clouds is a decision-making process. To measure the dimension of room, the most interior points are traced and measured. Taking the master bedroom height measurement as an example, the highest point describing the floor and the lowest point describing the roof were traced and measured (Figures 5-20, 5-21, 5-22).

In the case where ceiling, floor, wall, or the surface being capture is not straight, the measurement location should be the same to reduce human factor impact.

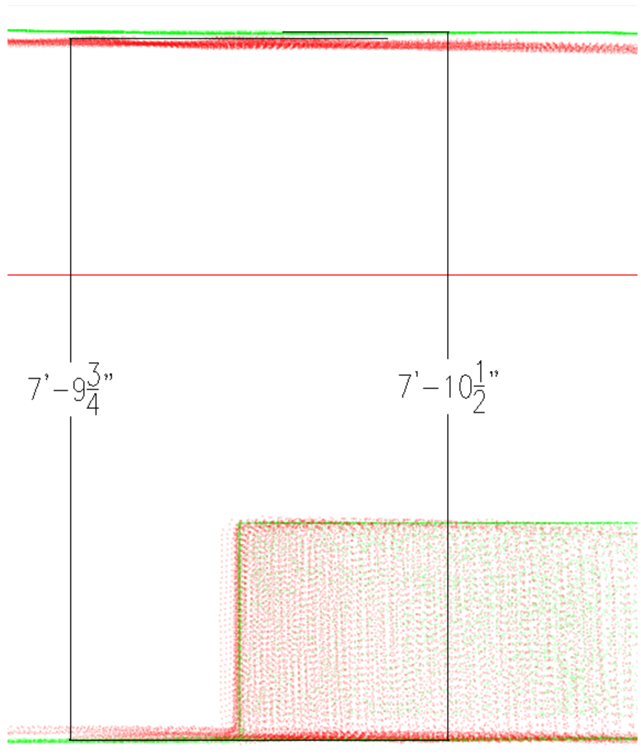


Figure 5-20: Master bedroom floor to ceiling measurement example

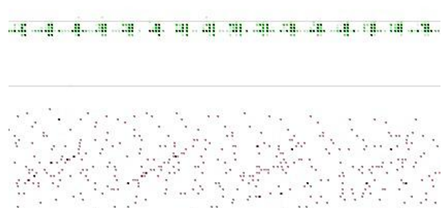


Figure 5-21: Master bedroom height measurement ceiling tracing detail. Lines traced the top of ceiling.

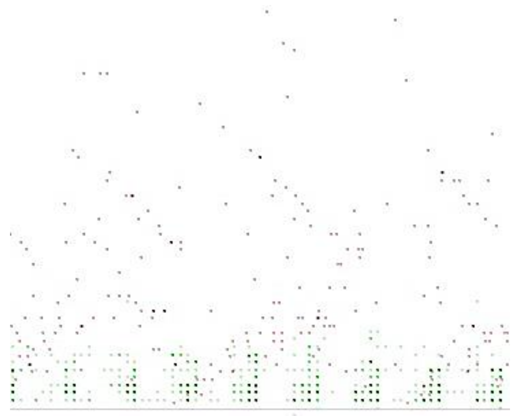


Figure 5-22: Master bedroom height measurement floor tracing detail. Lines traced the bottom of the floor.

The thickness of points in point clouds can impact tracing and measuring result. RTC 360 scanned point cloud shows a consistent thin layer of points, the top and bottom points are relatively easy to determine and trace (Figure 5-23). iPhone scanned data varies based on different point density. High point density mode results in a thicker layer of points (1/2 inch – 1 1/4 inch), low point density mode results in a thinner layer of points (1/4 inch – 1/2 inch). The thickness and fuzziness of points were impacted by distance and captured angle. The closer and more perpendicular to scanning target, the points will be thinner and organized. High density iPhone scans were fuzzier and denser, when zoom in it is easier to observe points. Low point density iPhone scan points were less concentrated with less floating points. Comparing to the consistence 1/8” thickness of RTC 360 scanned point cloud, iPhone scanned point clouds’ thickness are more irregular; in one scan, thickness can range from 1/4 inch to 1 1/4” inch. The fuzzy character of iPhone scanned point cloud create a difficulty in tracing because the majority of points are located in a densely described area, but a few points are flying around (Figure 5-24). There is no way to determine if the flying points are mis-captured fuzziness or an accurate capture. In this case, even the fuzzy points are questionable, they are still taking for tracing and measurement since the credibility is undistinguishable.

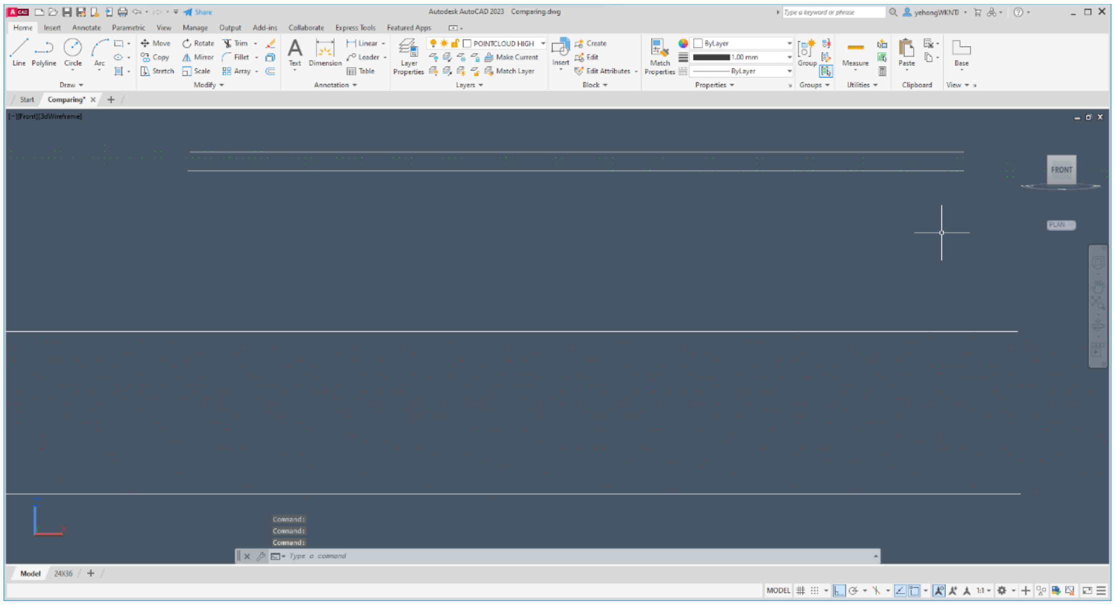


Figure 5-23: Tracing top and bottom points in section 2 with line command

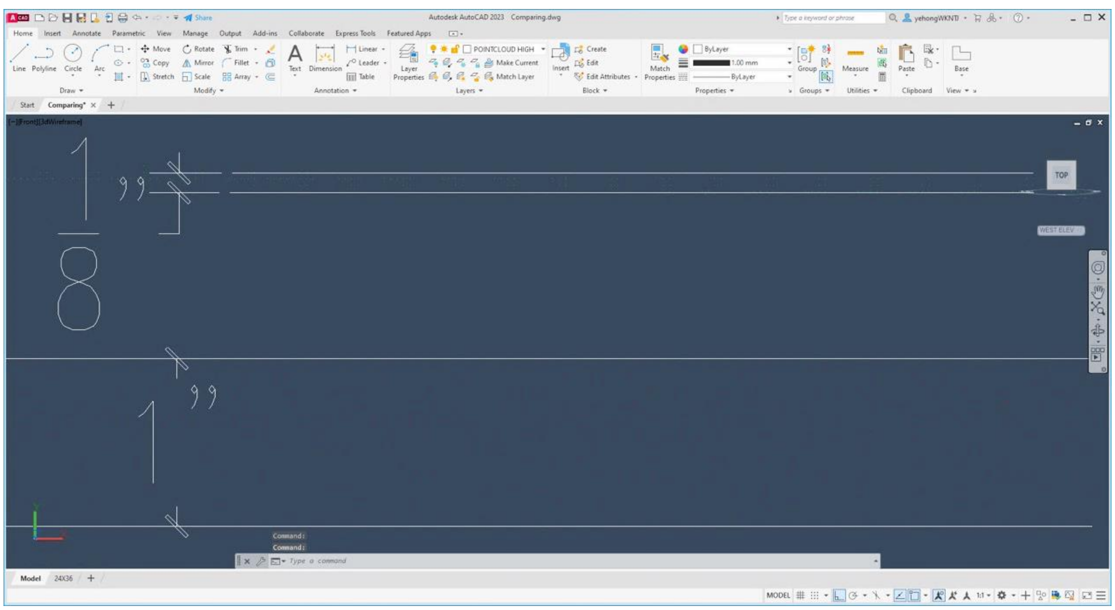


Figure 5-24: Measuring point thickness with dimensional tool. RTC 360 point cloud thickness is 1/8”, iPhone scanned point cloud thickness is 1”.

5.2.1 Smartphone scanned data results

The seven smartphone scans were processed through Autodesk Recap, which allowed for the data to be exported to rcp. files. These files were then imported into to AutoCAD, where all seven scans captured by the iPhone 13 Pro were measured using AutoCAD's dimensional tools.

Dimensions of room height, width, closet to closet distance, desk height and point cloud thickness were then compiled into tables (Tables 5-3 to 5-7). The measurements from table were used in comparison to measurements from the professional scanner and laser measurements to determine the accuracy of the scans and to assess the overall quality of the data.

Table 5-3: iPhone scanned high density point clouds measurements

iPhone High Density	Master Bedroom height	Master Bedroom Width	Master Bedroom Closet to Closet Distance	Desk Height	Point Clouds Thickness
Section 1	N/A	N/A	N/A	N/A	N/A
Section 2	7'-9 1/2"	N/A	N/A	N/A	1 1/4"
Section 3	7'-9 3/4"	N/A	N/A	2'-5"	2 1/2"

Table 5-4: Merged high density scans by iPhone measurements

iPhone High Merge	Master Bedroom height	Master Bedroom Width	Master Bedroom Closet to Closet Distance	Desk Height	Point Clouds Thickness
Section 1	N/A	15'-7 3/8"	N/A	N/A	N/A
Section 2	7'-8 5/8"	N/A	10'-10 5/8"	N/A	5/8"
Section 3	7'-9 3/4"	N/A	N/A	2'-5"	3/4"

Table 5-5: iPhone scanned low density point clouds measurements

iPhone Low Density	Master Bedroom height	Master Bedroom Width	Master Bedroom Closet to Closet Distance	Desk Height	Point Clouds Thickness
Section 1	N/A	15'-10 1/4"	N/A	N/A	N/A
Section 2	7'-11 1/4"	N/A	10'-8"	N/A	1 1/8"
Section 3	7'-9 5/8"	N/A	N/A	2'-5 1/2"	5/8"

Table 5-6: Merged low density scans by iPhone measurements

iPhone Low Merge	Master Bedroom height	Master Bedroom Width	Master Bedroom Closet to Closet Distance	Desk Height	Point Clouds Thickness
Section 1	N/A	15'-8 1/8"	N/A	N/A	N/A
Section 2	7'-11 1/4"	N/A	10'-8 7/8"	N/A	1 1/2“
Section 3	7'-11 1/4"	N/A	N/A	2'-4 5/8"	1 5/8"

Table 5-7: Merged floorplan measurements

iPhone Merged Floorplan	Master Bedroom height	Master Bedroom Width	Master Bedroom Closet to Closet Distance	Desk Height	Point Clouds Thickness
Section 1	N/A	15‘-9 5/8	N/A	N/A	N/A
Section 2	7'-11 3/8"	N/A	10'-8 7/8"	N/A	1 1/4”
Section 3	7'-11 1/4"	N/A	N/A	2'-5 1/8"	3/4"

5.2.2 Professional scanner scanned data results

A 3D laser scan was done with a Leica RTC 360 LiDAR scanner by Alan D. White. Three scans were captured with the 3D scanner set on a tripod at three different locations in the master bedroom. The point clouds were registered in Leica Cyclone software and translated to an RPC file in Recap. Measurements were then taken using AutoCAD tools (Table 5-8). The data obtained from this professional scanner was used as a ground truth for comparison with data obtained from a smartphone scanner. This comparison will help to evaluate the accuracy of the smartphone scanner.

Table 5-8: Leica RTC 360 scan measurements

Leica RTC 360	Master Bedroom height	Master Bedroom Width	Master Bedroom Closet to Closet Distance	Desk Height	Point Clouds Thickness
Section 1	N/A	15’-9 1/8”	N/A	N/A	N/A
Section 2	7’-10 1/2”	N/A	10’-8”	N/A	1/8”
Section 3	7’-10 1/2”	N/A	N/A	2’-5”	1/8”

The scanner was set to low density mode during capture; a thin layer of points were exhibited in the point clouds (Figure 5-25) The thickness of data is 1/8” and remained stable in the whole point cloud.

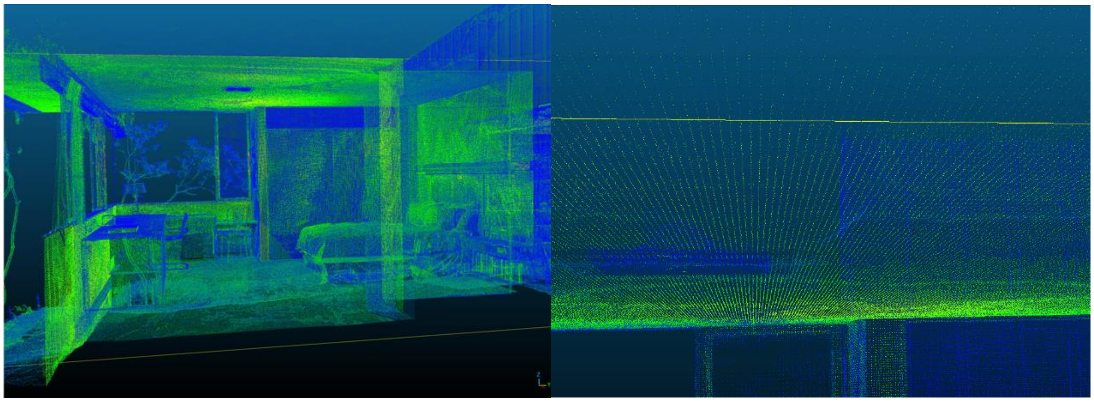


Figure 5-25: Layer of points from Leica RTC 360

5.3 Result comparison between iPhone and Leica RTC 360

Dimensional data exhibited in previous table (Table 5-1 – 5-6) were reorganized for comparison and calculating error. Observation in visual comparison between RTC 360 point cloud and iPhone scanned point clouds were shown through screenshots.

5.3.1 Measurements and errors

The measurement results from iPhone 13 Pro were compared to the data acquired from professional scanner RTC 360 individually and compared (Tables 5-9 to Table 5-14). Point cloud acquired by Leica RTC 360 was imported to AutoCAD and used as the ground truth values.

Table 5-9: Room width measurements comparison in section 1

Section 1	RTC 360	iPhone High Density	iPhone High Merge	iPhone Low Density	iPhone Low Merge	iPhone Floorplan
Room Width	15'-9 3/4"	N/A	15'-7 3/8"	15'-10 1/4"	15'-8 1/8"	15‘-9 5/8
Error		N/A	1 7/8"	1/2"	1 5/8"	1/2”
1/2"		N/A	x	√	x	√
3/16"		N/A	x	x	x	x
2 2/5"		N/A	√	√	√	√
Error Percentage		N/A	0.94%	0.26%	0.86%	0.26%

The percentage of error was calculated through dividing difference between iPhone scanned point clouds and RTC 360 scanned clouds by the room width measured from RTC 360 scanned data. The highest percentage of error happened with merged high point density scan in 0.94% within a range of 15 foot. The lowest percentage of error occurred in low point density scan in 0.36%.

Table 5-10: Room height measurements comparison in section 2

Section 2	RTC 360	iPhone High Density	iPhone High Merge	iPhone Low Density	iPhone Low Merge	iPhone Floorplan
Room Height	7'-10 1/2"	7'-9 1/2"	7'-8 5/8"	7'-11 1/4"	7'-11 1/4"	7'-11 3/8"
Error		1”	1 7/8”	3/4”	3/4”	7/8"
1/2"		x	x	x	x	x
3/16"		x	x	x	x	x
2 2/5"		x	x	√	√	√
Error Percentage		1.06%	1.98%	0.79%	0.79%	0.93%

The percentage of error of room height measurement was calculated in section 2. The result shows smartphone scan in low point density without process have the closest measurement to the scanner scan. The largest error percentage was shown in iPhone scanned data in high density, then merged. High density scan demonstrates a higher error rate than low density scan, which represent a larger deviation from scanner data. Even though iPhone high merge, iPhone low merge, and iPhone floorplan were all merged scans, there are differences in the percentage of error. The result shows error in iPhone low density < iPhone low merge < error in iPhone floorplan < error in iPhone high density < iPhone high merge.

Table 5-11: Bedroom width 2 measurements comparison in section 2

Section 2	RTC 360	iPhone High Density	iPhone High Merge	iPhone Low Density	iPhone Low Merge	iPhone Floorplan
Bedroom Width 2	10'-8"	N/A	10’-10 5/8”	10’-8”	10'-8 7/8"	10'-8 7/8"
Error		N/A	2 5/8"	0	7/8”	7/8”
1/2"		N/A	x	√	x	x
3/16"		N/A	x	√	x	x
2 2/5"		N/A	x	√	√	√
Error Percentage		N/A	2.05%	0	0.68%	0.68%

Error and error rate in bedroom width 2 measures are shown in table (Table 5-7). Low point density iPhone scanned data exhibited a same measurement with the Leica RTC 360 scan, achieving a 100% accuracy for a 10 foot distance. The merged floor plan scan from iPhone has a 0.68% of error, and the merged low point density scan from smartphone has a 0.68% of error. The largest deviation was shown in the merged high point density scan from iPhone with a 2.05% of error from professional scanner data.

Table 5-12: Room height measurements comparison in section 3

Section 3	RTC 360	iPhone High Density	iPhone High Merge	iPhone Low Density	iPhone Low Merge	iPhone Floorplan	Floor to Ceiling
Room Height	7'-10 1/2"	7'-9 3/4"	7'-9 3/4"	7'-9 5/8"	7'-11 1/4"	7'-11 1/4"	7'-11"
Error		3/4"	3/4"	7/8"	3/4"	3/4"	1/2"
1/2"		x	x	x	x	x	x
3/16"		x	x	x	x	x	x
2 2/5"		√	x	x	x	x	√
Error Percentage		0.80%	0.80%	0.93%	0.80%	0.80%	0.53%

In the measurement of room height from section 3, high density scan and floor to ceiling scan from iPhone shows the smallest error in 1/2", resulting in 0.53% of error in 7'-10 1/2". The largest deviation is exhibited in merged low density scan from smartphone, causing 0.93% of error rate.

Table 5-13: Desk height measurements comparison in Section 3

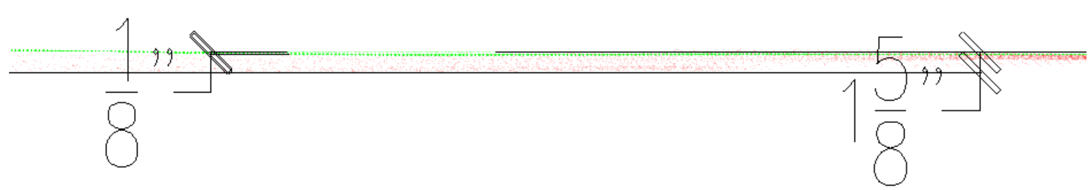
Section 3	RTC 360	iPhone High Density	iPhone High Merge	iPhone Low Density	iPhone Low Merge	iPhone Floorplan	Floor to Ceiling
Desk Height	2'-5"	2'-5"	2'-5"	2'-5 1/2"	2'-4 5/8"	2'-5 1/8"	2'-5 1/4"
Error		0	0	1/2"	3/8"	1/8"	1/4"
1/2"		√	√	√	√	√	√
3/16"		√	√	x	x	√	x
2 2/5"		√	√	√	√	√	√
Error Percentage		0	0	1.7%	1.3%	0.43%	0.86%

The error and error rates of desk height from section 3 was measured and calculated. High density scan and merged high density scan reach 0 inch in error (with an accuracy of 1/8"). The merged floorplan shows a 0.4% of error with 1/8" of deviation, floor to ceiling scan achieved 0.9% of error with 1/4" of deviation. The performance of low density scan and merged low density scan demonstrated 1.7% and 1.3% of error, which represent more deviation from the scanner data.

Table 5-14: Point cloud thickness comparison in section 2 and 3

Point Clouds Thickness	RTC 360	iPhone High Density	iPhone High Merge	iPhone Low Density	iPhone Low Merge	iPhone Floorplan
Section 2	1/8"	1 1/4“	5/8”	1 1/8”	1 1/2“	1 1/4”
Section 3	1/8"	2 1/2”	3/4”	5/8"	1 5/8"	3/4"

Comparison in point cloud thickness were made in section 2 and 3. Points from RTC 360 scanner show a consistent pattern and a stable thickness of 1/8” The performance of smartphone acquired points are more fuzzy and more irregular (Figure 5-26).



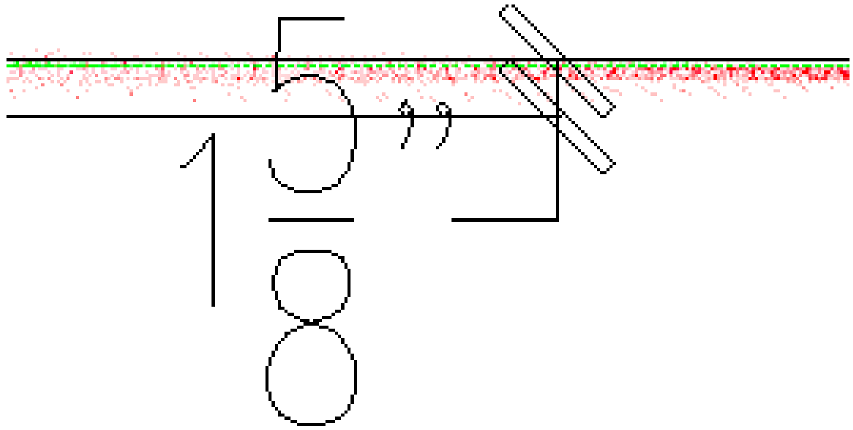


Figure 5-26: Ceiling detail in low point density scan section 2. Green representing RTC 360 scanner data, red representing iPhone scanned data. The thickness of scanner points is 1/8”; the thickness of iPhone scanned points is 1 5/8”

The result from the comparisons reveals a pattern of low point density scans achieving better results than high point density scans, and raw data performing better than merged files. The high point density scan error rated from 0 to 1.06%, high point density merged scan error rated from 0 to 2.05%, low point density scan error rated from 0 to 1.72%, low point density merged scan error rated from 0.68% to 1.29%. Scanned data with original low point density mode has the best performance with the least error rate and stabled measurements. Qualification of each mode of smartphone scans for heritage conservation purposes and scales will be discussed in 5.3.2.

5.3.2 Visual comparison

Point clouds captured from iPhone with various parameters and set ups were imported and aligned to the ground truth. Three section views (plans) were created to visualize the deviations and differences between professional scanner scanned data and iPhone scanned data.

Scanner and iPhone acquired point cloud thickness of bedroom ceiling are visualized (Figure 5-27). In the case of Reunion House, both scanner and iPhone captured the slope of the roof. The professional scan described the surface with one layer of clean points. The iPhone captured geometry is fuzzy and hard to recognize. As section 5.2 introduced, the fuzziness of points obtained by smartphone cause difficulties in determine the accurate location of surfaces. Tracing the lowest point of ceiling for measurements can be a possible reason for errors and impacting factor of accuracy.

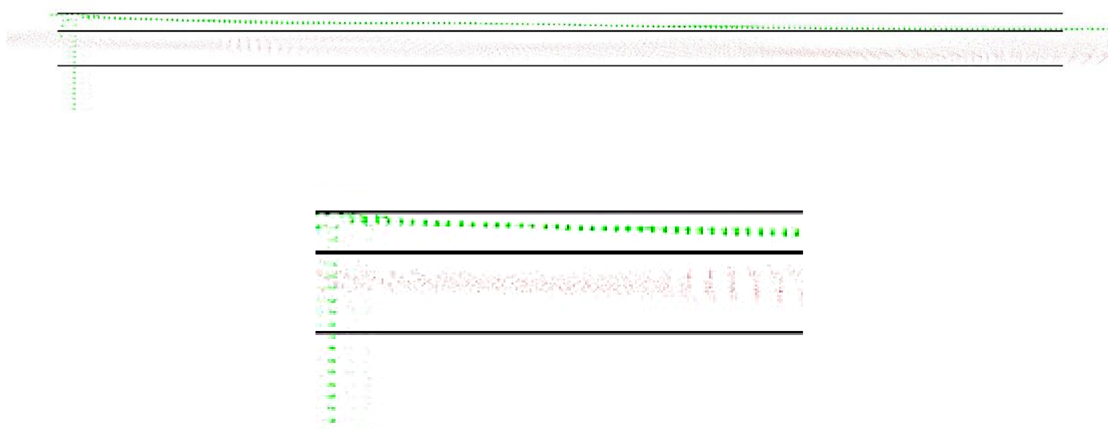


Figure 5-27: High density iPhone scan (red) and RTC 360 scan (green) ceiling detail

The detail of a low-density iPhone scan is shown aligned with the point cloud from the professional scanner in Section 2 (Figure 5-28). The detail section view described the thickness of a sliding closet door. The green point cloud (RTC 360) displays two surfaces, and the thickness of the red point cloud is the distance between them. The red point cloud is accurately picturing the structure and thickness, however, without the aid of the professional scanner data, this information would be difficult to interpret. It requires heritage conservation professionals having access to site when reading point clouds, or heritage conservation professionals being very familiar to the site, to read and understand such detail.

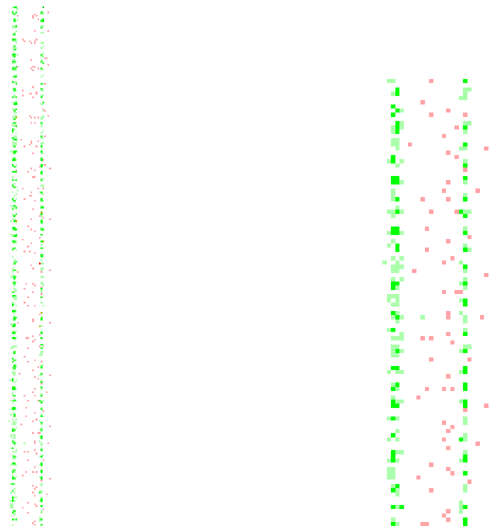
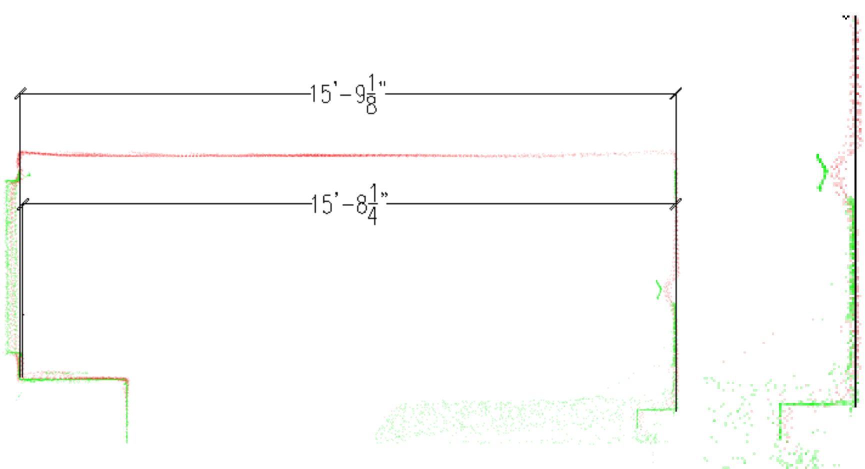


Figure 5-28: Low density iPhone scan (red) and RTC 360 scan (green) closet detail

The iPhone scan exhibited a deficiency in describing details. The lighting structure on the right wall from section 1 was described differently in professional scanner point cloud and the iPhone point cloud. The structure of lighting was described clearly from professional scanner, while the iPhone captured a rough shape at the accurate location (Figures 5-29 and 5-30). Even though not able to capture detailed geometry, the observation supported smartphone device’s ability to describe feature location, which can be used in assisting heritage conservation tasks.



Figures 5-29 and 5-30: Low density iPhone scan (red) and RTC 360 scan (green) section 1 (left), and detail (right).

From the section views, it was obvious that smartphone was struggled to capture corners. In the example from merged scan of high point density scan, the roof to wall corner were described as a round turn instead of a sharp ninety degree angle (Figure 5-31). In comparison, the corner of drawer meeting ground was described shapely. This might be impacted by distance factors that in a merged scan, three scans from lower angle, level, and upper angle are piecing together. The scanning device is closer to ground than to ceiling; smartphone camera was also facing ground target more perpendicular than facing roof.

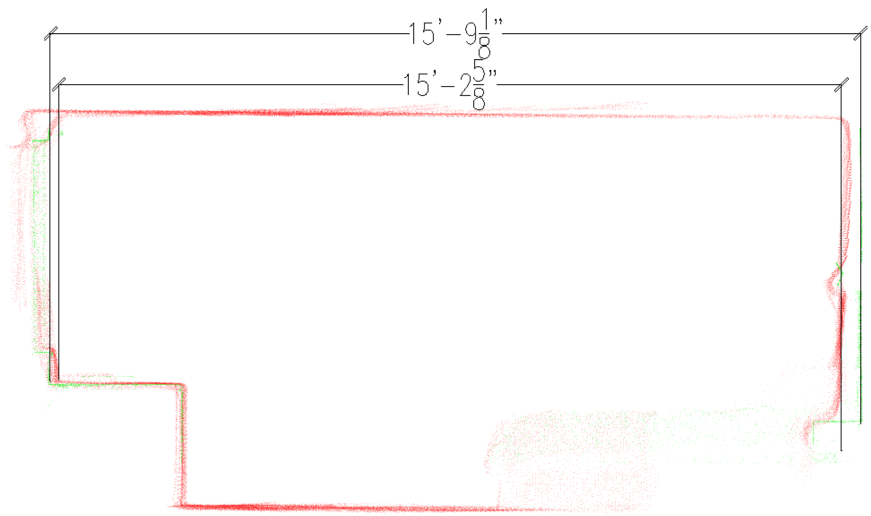


Figure 5-31: Merge of high point density scans from smartphone aligned with professional scanner point clouds

5.4 Qualification

Based on the deviations measured from smartphone scans and professional scanner scans, low point density scan by smartphone achieved acceptable accuracy/precision in desk height, and bedroom width 2 distance for architectural drawing scale 4/1"=1'-0". Merged floorplan scan achieved acceptable accuracy/precision in desk height and room width measurements. Floor to ceiling scan achieved 1/4" in desk height. None of the room heights were measured accurately enough for creating an architectural drawing. With some target measurement laying outside the acceptable range, low point density scan acquired from iPhone achieved error rates from 0 to 1.72% (Table 5-15). Bedroom width 2 distance lays in an acceptable range of error as an alternative digital documentation method. Desk height, room heights, and width measurement are not precise enough as a laser scan with the current method.

Table 5-15: Smartphone scan low density mode error rate

Low Density					
	Desk Height	Room Height Section 3	Room Width 2	Room Height Section 2	Room Width
Error	1/2"	7/8"	0	3/4”	1/2"
1/2"	√	x	√	x	√
3/16"	x	x	√	x	x
Error Rate	1.72%	0.93%	0.00%	0.79%	0.26%

Merged low density scans achieved error rates from 0.68% to 1.29% (Table 5-16). The least deviation happened with the measurement of desk height, meeting architectural scale 1/4” = 1’-0” smallest unit. The most deviation occurred in room height. Scan measurements except for desk height do not meet drawing standard. None of the measurement meet laser scan standard.

Table 5-16: Smartphone scan low density mode merged error rate

Low Density Merge					
	Desk Height	Room Height Section 3	Room Width 2	Room Height Section 2	Room Width
Error	3/8"	3/4”	7/8”	3/4”	1 5/8"
1/2"	√	x	x	x	x
3/16"	x	x	x	x	x
Error Rate	1.29%	0.80%	0.68%	0.79%	0.86%

High density scans achieved error rates from 0.0% to 1.06% (Table 5-17). Desk height reaches the standard for common architectural scale, but desk height and room height do not meet laser scan accuracy standard.

Table 5-17: Smartphone scan high density mode error rate

High Density					
	Desk Height	Room Height Section 3	Room Width 2	Room Height Section 2	Room Width
Error	0	3/4"	N/A	1”	N/A
1/2"	√	x	N/A	x	N/A
3/16"	√	x	N/A	x	N/A
Error Rate	0	0.80%	N/A	1.06%	N/A

Merged high density scans achieved error rates from 0 to 2.05% (Table 5-18). Same as low point density mode, desk height appeared meeting common architectural drawing scale, but none of the measurements can be used to determine the smallest unit for architectural scale 1/4”=1’-0”.

Table 5-18: Smartphone scan high density mode merged error rate

High Density Merge					
	Desk Height	Room Height Section 3	Room Width 2	Room Height Section 2	Room Width
Error	0	3/4"	2 5/8"	1 7/8”	1 7/8"
1/2"	√	x	x	x	x
3/16"	√	x	x	x	x
Error Rate	0	0.80%	2.05%	1.98%	0.94%

Merged scan floorplan achieved error rates from 0.0% to 2.05% (Table 5-19). Merged floorplan scans have the least deviation with desk height, then room width. Both measurements meet common architectural drawing scale; measuring feature such as desk height can even be used for door/window drawing. Room height and closet to closet distance, however, do not meet common drawing scale smallest unit identify standard and digital documentation scale.

Table 5-19: Smartphone scans merged floor plan error rate

Floorplan					
	Desk Height	Room Height Section 3	Room Width 2	Room Height Section 2	Room Width
Error	1/8"	3/4"	7/8”	7/8"	1/2”
1/2"	√	x	x	x	√
3/16"	√	x	x	x	x
Error Rate	0.43	0.80%	0.68%	0.93%	0.26%

The measurement of desk height for the five methods (low point density, merged low point density, high point density, merged high point density, and merged floorplan) can be used to identify the smallest unit for common architectural drawing scale, merged, high point density, and floor plan measurements of desk height even can be used to determine the smallest unit for scale used on window and door drawings. Thus, smartphone scans with tripod are approved for the documentation, survey, and monitoring of furniture size architectural features.

In the measurement of room dimension, smartphone scans have limited ability. With raw scan data, low point density is closer to the ground truth; the merged high point density scan has the most deviation from the ground truth. None of smartphone scans measurements of room height, width, or closet to closet distance reached professional scanner's accuracy of 1/8". Therefore, with current methodology smartphone scan is not a recommend substitute for professional scanner scan in creating architectural drawings.

Further improvements in methodology can be made to make the results more accurate. In the current method, alignment in AutoCAD is done manually, which may cause deviation. Even though iPhone scans were registered as close as possible to the professional scanned point cloud, the manual operation can still cause a range of mistakes. Moreover, when measuring surface to surface distance, angled surfaces with different measure points can result difference in dimensions. Further research should be done to discover best how to control measuring points. Additionally the fuzzy quality of the smartphone scanned point clouds increase tracing error caused by human decisions on where to draw the lines.

Even though not as accurate and precise as professional scanner, smartphone scan takes advantage on being able to handheld. Professional scanners on tripod can have shadow, where laser light cannot reach therefore creating a blank area in point clouds. By having a smartphone handheld, moving around a target when scanning, the shadow can be reduced or avoided.

Thus, smartphone scanned point clouds are not qualified for professional purposes of heritage conservation unless further research being conducted to rule out errors caused by human decisions in measuring procedure. The current research result supports smartphone scanned point clouds as interpretive drawing, or as assistant document provide alongside hand measurements. The instability reduced the reliability of smartphone scanning of heritage conservation for professional uses. In case of endangered heritage and heritage at inaccessible locations, a smartphone scanned documentation can provide a relatively quick although not as accurate documentation.

5.5 Summary

Chapter 5 exhibited the scanning result of smartphone scans.

- 5.1 introduced commonly used architectural drawing and digital documentation scale and selected the standard for the evaluation of iPhone scans.
- 5.2 mentioned the measurements and result of three methods including smartphone scan, professional scan, and laser measurements.
- 5.3 comparisons made; they were divided into two parts, numeric comparison and visual comparison. Measurement results were compared on each scanning target.
- 5.4 evaluated the qualification of different modes of smartphone scans.

iPhone acquired scans and professional scanner captured scans were exported from the scanning software and imported into AutoCAD so that measurements could be made. Potential error from human interpretation were observed from 1) manual alignment process in measurements, 2) different measurement setpoints on angled surfaces (walls, ceiling, and floor), 3) distinguishing fuzzy points from captured surface in point clouds. Sections were created in measure room dimensions. The percentage of error of each target was calculated. Smartphone scans on furniture scale met architectural drawing standard for heritage conservation purposes. On room or building scale, the quality of data was doubted with deviation exceeding 1/2 of the smallest unit needed for heritage conservation tasks. Using low point density mode can achieve a better result with a smaller rate of error, and raw data performing better than merged files.

Through visual comparison, the result shows smartphone can capture a slightly tilted surface, but the thickness of points are thicker than professional scanners. iPhone LiDAR scanned architecture detail include the correct location but lack a clear description of the geometry. The capture and exhibition of wall intersection and corners from iPhone is a rounded corner instead of a 90 degree angle. Because light travels in straight lines, professional and smartphone scans taken on tripod will always have shadow in documentation. Handheld smartphone scan can reduce shadow through moving around targets in capturing from maximum angle.

With human factors and objective factors impacting scanning result, and improvements to be made, there is still the possibility for smartphone scanned data qualified for room and building scale architectural drawings. Suggestions and potential usages of smartphone acquisition on heritage conservation will be discussed further in Chapter 6.

Chapter 6 Qualification

Chapter 6 examines a smartphone scanned data's application to the four heritage conservation tasks: documentation, survey, monitoring, and education (Figure 6-1). The accuracy of the data collected by smartphones are compared against the traditional methods for these tasks. It also looks at the advantages and disadvantages of using smartphones for heritage conservation tasks and the challenges associated with it. The chapter also provides recommendations for best practices for using smartphones in conservation tasks. Finally, the chapter discusses future research directions and technologies that could further improve the use of smartphones in heritage conservation tasks.

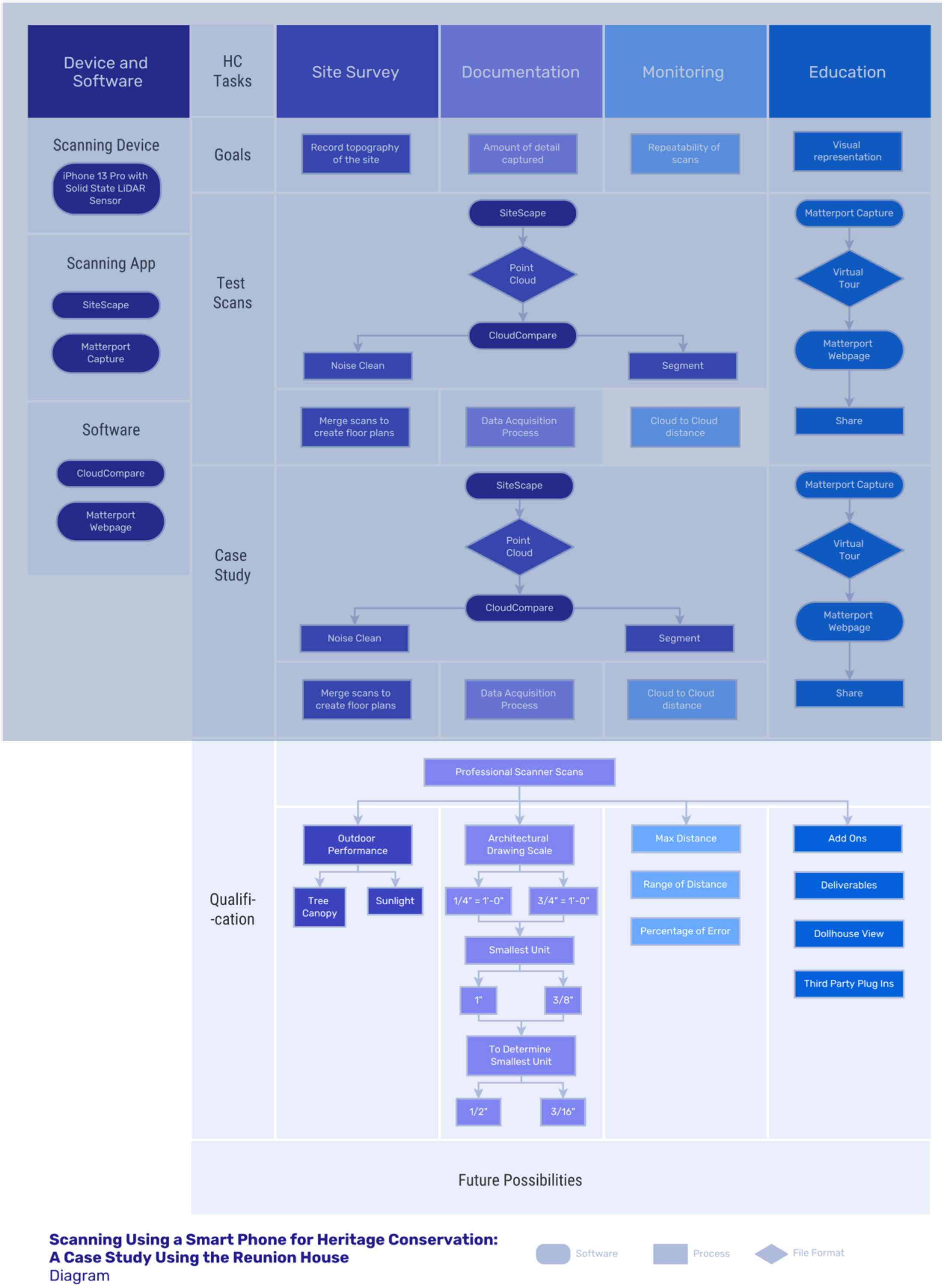


Figure 6-1: Chapter 6 overview diagram

6.1 Documentation

The qualification of scanned data from smartphones for heritage conservation documentation was based on the HABS (Historic American Buildings Survey) requirement of paper submissions (Library of Congress, 2016). The size of the paper and the line weight were considered as impacting factors, which are dependent on the scales used. As of now, the final output is expected to be a paper drawing with a specific scale, which can be either generated from point clouds that handed over directly to architects or directly traced by heritage conservation professionals.

The most common architectural scales for smaller building components, 1/4”=1’-0” and 3/4”=1’-0” were selected as the standards for the qualification of smartphone scanned data (Table 6-1). Smartphone scans were manually aligned with professional scanners’ scan in AutoCAD. Data acquired from professional scanners were considered as ground truth in the comparison (Figure 6-2). Smartphone scans were measured and compared to the ground truth; errors and error rates were calculated as result. Qualification standards were determined based on half of the smallest units of the two common architectural scales (1/2” and 3/16”).

Table 6-1: Architectural Scales for drawing (Burns, 2004)

Scale	Smallest Unit	Evaluating Unit	Use
1/16" = 1'-0"	4"	2"	Drawings of large structures without details. Materials shown in plan only.
1/8"=1'-0"	2"	1"	Little detail possible. Materials shown in plan, only large units in elevation.
1/4"=1'-0"	1"	1/2"	Common architectural scale. Reasonable amount of detail possible. HABS/HAER shows door and window frames, materials in both plan and elevation. At this scale, line weights can adversely affect accuracy. A 3x0 (0.25 mm) line is approximately 1/2" thick.
3/4"=1'-0"	3/8"	3/16"	Common scale for door/window elevations and other features of similar scale.
1 1/2"=1'-0"	3/16"	3/32"	Details of door/window jambs/frames, large tools, small machines, etc.
3"=1'-0"	3/32"	3/64"	Details of objects such as hardware, tools, etc. and molding profiles.
Full Size			Small or intricate objects, elaborate moldings and ornamentation

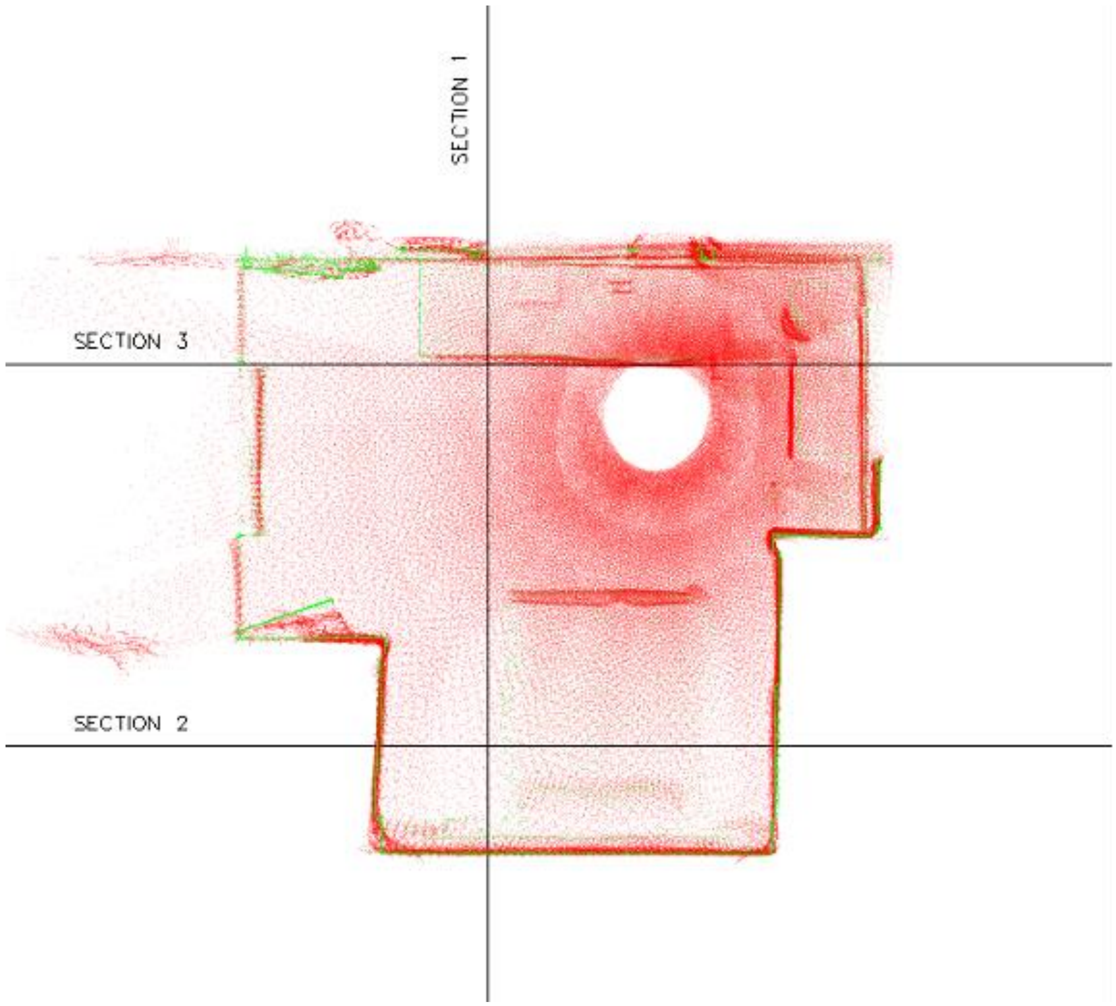


Figure 6-2: Smartphone scans were manually aligned with professional scanners' scan in AutoCAD. Green point cloud from RTC 360, red point cloud from iPhone

Smartphone scans with SiteScape exhibited a good result in the measurement of furniture, door, and window size target at 1/4"=1'-0" scale. In scans with either high or low point density mode, errors in these measurements ranged smaller than 1/2" and bigger than 3/16" (see Chapter 5.3.1). This means smartphone can be used to measure such targets in a drawing that commonly describe rooms and floorplans. In the measurement of room dimensions in scale 1/4"=1'-0", low point density mode exhibited limited errors in the measurements of two room widths, nevertheless, two room height measurements fall out of the qualification standards.

Horizontal acquisitions were observed as being more accurate than vertical acquisitions in high point density mode and merged scans, which may because smartphone device was turning horizontally during acquisition, and the laser can shoot better perpendicularly on vertical walls than roof and floor. When the laser was shot on a surface with small angle, the accuracy can be reduced, which also happened to professional scanners. Unfortunately, most of the acquisitions were not accurate enough for scale 3/4”=1’-0” scale, which most commonly used in documenting window and door details.

From visual comparison, smartphone scans can document the thickness of door panels, angled surfaces, and locations of detail features (see Chapter 5.3.2) (Figures 6-3, 6-4, 6-5). The thickness of bedroom closet sliding door was accurately described by both professional scanners and smartphone, although with different expression of points. The slopped roof of bedroom was also recorded by smartphone scans. Geometries of small features such as lighting fixtures cannot be recorded, but the location can be accurately described in sections views.

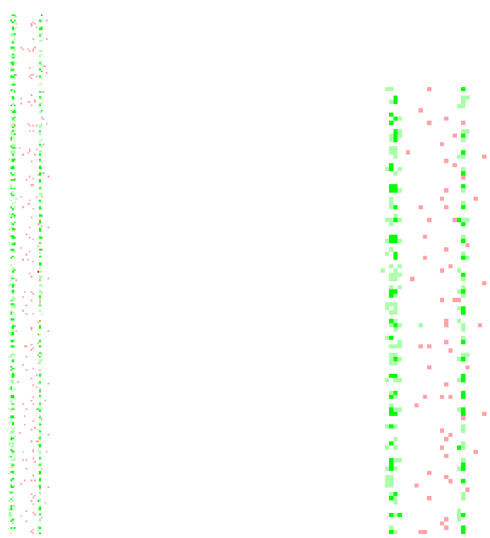


Figure 6-3: Low density iPhone scan (red) and RTC 360 scan (green) closet detail

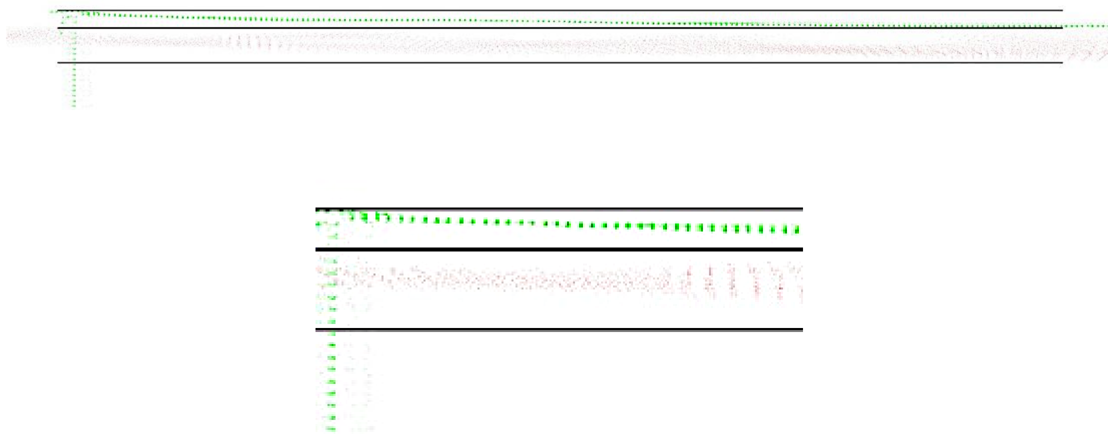
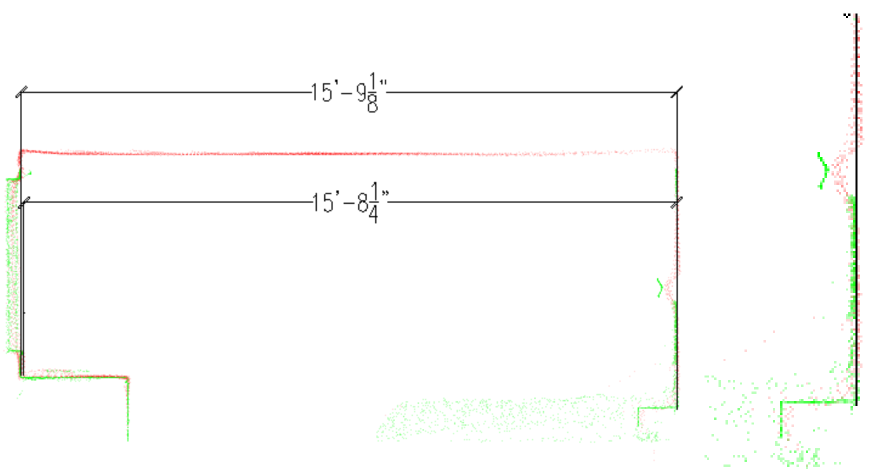


Figure 6-4: High density iPhone scan (red) and RTC 360 scan (green) ceiling detail



Figures 6-5: Low density iPhone scan (red) and RTC 360 scan (green) section 1 (left), and detail (right).

The same as a professional scanners' limitations, mirrors and glazing are problematic for smartphone to scan as well. For example, the iPhone laser reflects on a mirror, shoots to the bathroom wall, and is reflected back, creating a space in the mirror that doesn't exist in real environment (Figure 6-6). Window glazing caused laser refraction and deviation on acquisition (Figure 6-7). Thus everything acquired through mirror and glazing needs to be cropped during data processing.

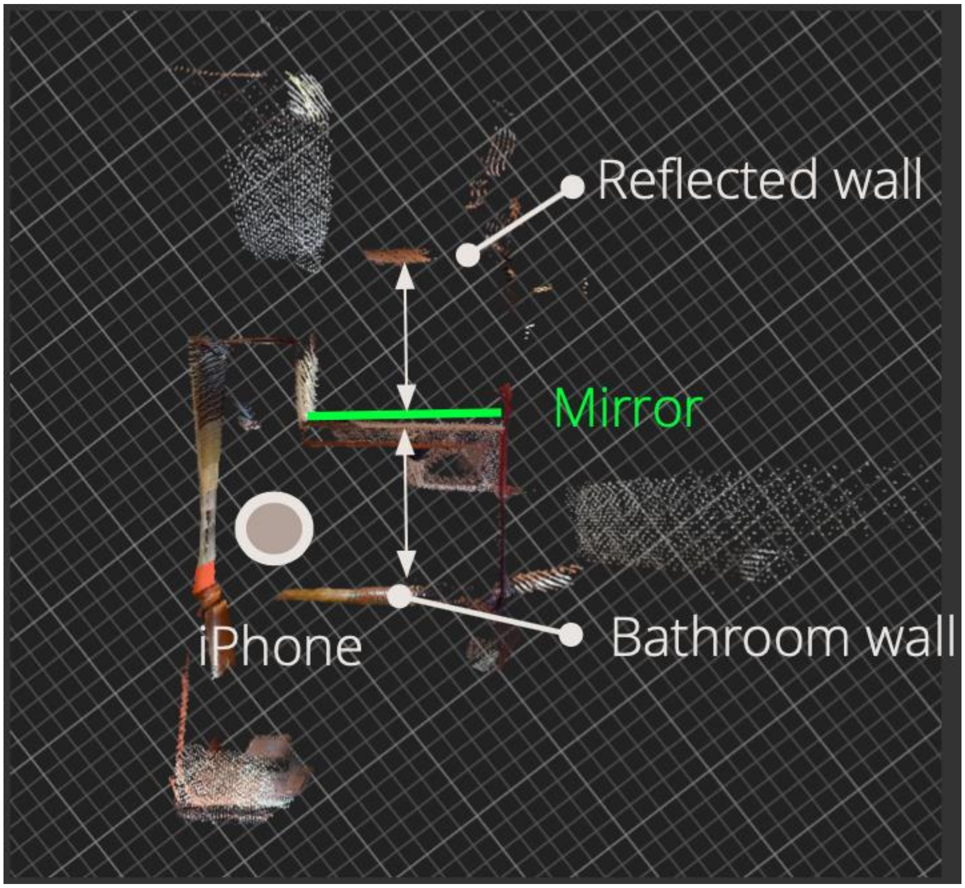

Reflected wall
Mirror
iPhone
Bathroom wall

Figure 6-6: Mirror reflection captured by smartphone

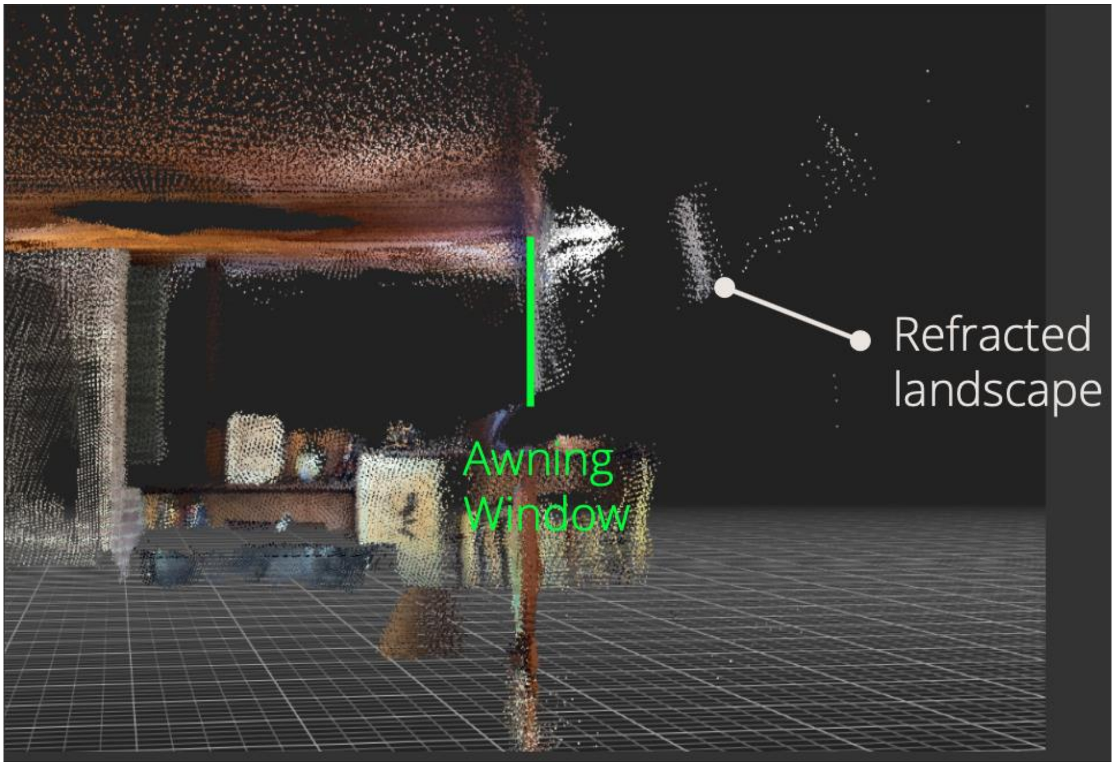


Figure 6-7: Refracted landscape captured through awning windows in Reunion House living room.

Models can also be traced from scanned point clouds. The accuracy of 3D models generated from point clouds depends on the quality of the data used. Therefore, it is important to use reliable scanners to generate the most accurate 3D models. In the case of smartphone scans, the error range of smartphone scan is laid between 0 inch to 2 5/8" inch within measurements of 2’-5” to 15'-9 1/8" (see Table 5-15 to Table 5-19). Compared to professional scanners, which can limit error to less than 1/8”, smartphone scans are not suitable for heritage conservation professionals to use as a reliable source for tracing and creating 3D models that are up to HAB’s standards, but could be used if lower accuracy is acceptable.

Merging scans manually in CloudCompare can create a floor plan of a single family house sized building, but this process can be prone to errors. While the accuracy of the floor plan is usually satisfactory if the plan is in a loop, its accuracy can suffer if it is linear. Point clouds acquired from professional scanners also need merging, however, the paid software did a better job than manual alignment and merging.

To serve heritage conservation documentation, smartphone scans can be used in documenting location of features such as furniture, doors, and windows with architectural scale 1/4”=1’-0”. However, room size and dimensions are not recommended using smartphone scan. iPhone scans are not accurate enough for measuring room dimensions in scale 1/4”=1-0”, and for window and door detail drawing with scale 3/4”=1’-0”. With different scanning parameters in SiteScape, low point density achieves better result than high point density. Raw scan data had better results than merged scans. Scanning angle and path also impact the accuracy of acquisition. Facing smartphone LiDAR sensor as perpendicular as possible to the scanning target can help secure accuracy as researched. For creating 3D models as documentation, smartphone scans are not accurate enough for tracing because the deviations are too big.

6.2 Survey

A smartphone scan is not suitable for generating a site survey for the Reunion House because it has various limitations that make it difficult to capture and accurately map the outside environment. For the lot at the Reunion House, too many stiches of scans was required to create a site survey because the limited range of smartphone scan acquisition. Different from indoor environments that have straight walls and solid volumes, an exterior environment are more organic and complex. In such environment reference targets using for scan merging and stitching are not offered, thus impacting quality of survey map. Furthermore, smartphone LiDAR struggles to capture data accurately in environments with a high tree canopy, as the LiDAR sensor on a smartphone is not powerful enough to penetrate the gaps between the leaves, meaning it often misses parts of the environment that need to be surveyed (Figures 6-8, 6-9, 6-10). This is especially problematic for Reunion House as it is located in a densely wooded area. In addition to the limited range and difficulty in stitching scans, smartphone LiDAR sensors are also susceptible to interference from external factors. In outdoor environments, the sensor is impacted by glare from the sun, which can cause distortion in the acquired data and render it unusable.

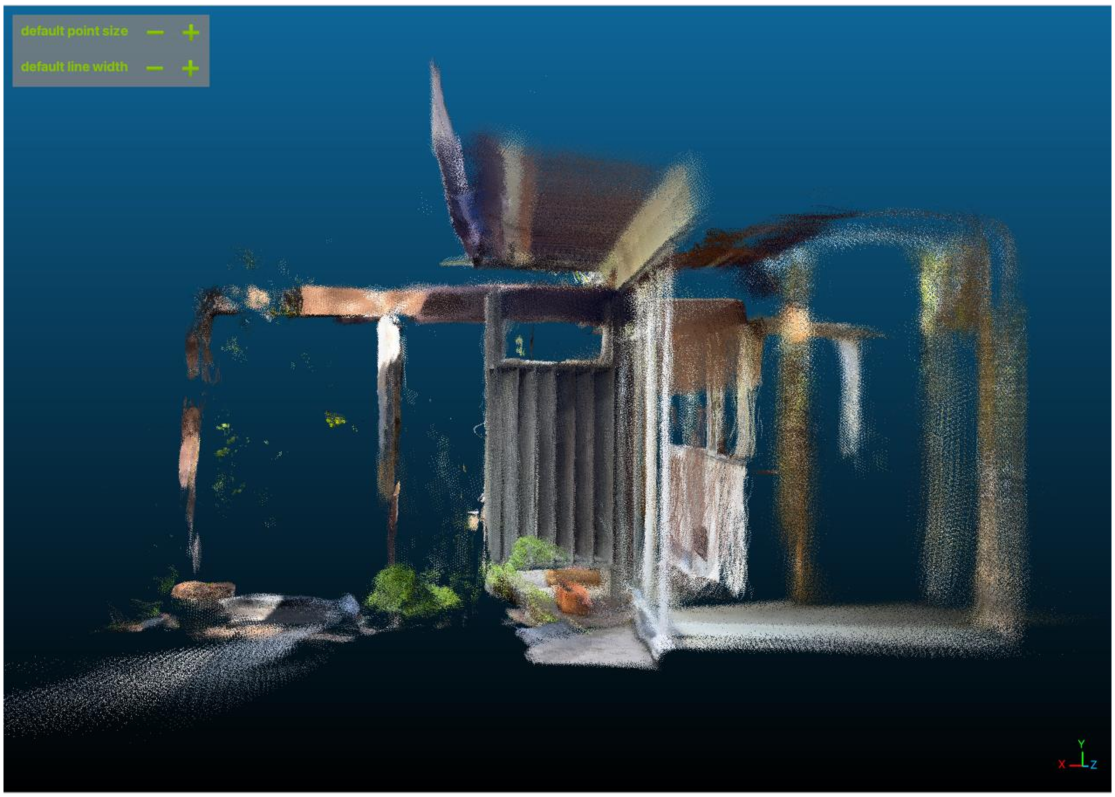


Figure 6-8: iPhone scanned front yard at Reunion House with a “spider leg” feature.

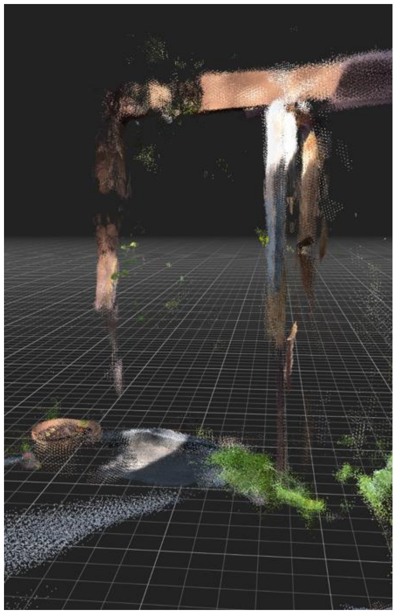
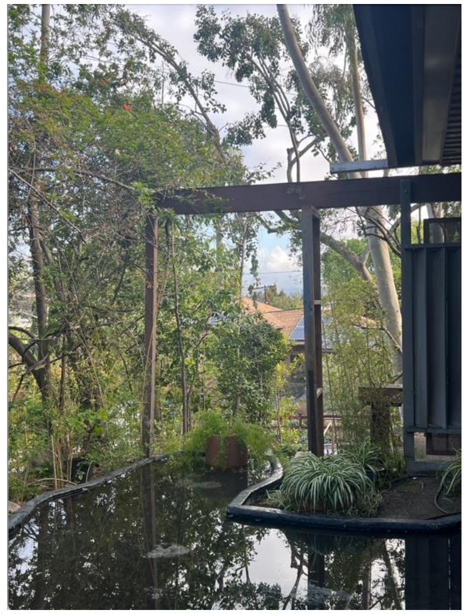
 

Figure 6-9: “Spider leg” feature detail in iPhone captured point cloud.

Figure 6-10: “Spider leg” feature photograph.

Professional scanners like the RTC 360 are designed with advanced technology that can handle complex outdoor environments with high tree canopy areas, strong sun light, and other environmental conditions (Figures 6-11, 6-12). That scanner is equipped with a high-powered laser system that can accurately and quickly scan the environment with enough amount of strong laser light penetrate tree canopy reaching ground or building surfaces. The scanner also has multiple sensors that can detect any obstacles in the environment, such as trees, buildings, and other objects. Additionally, the scanner was more stable under strong sunlight or insufficient lighting condition.

Figure 6-11: RTC 360 works outdoor.

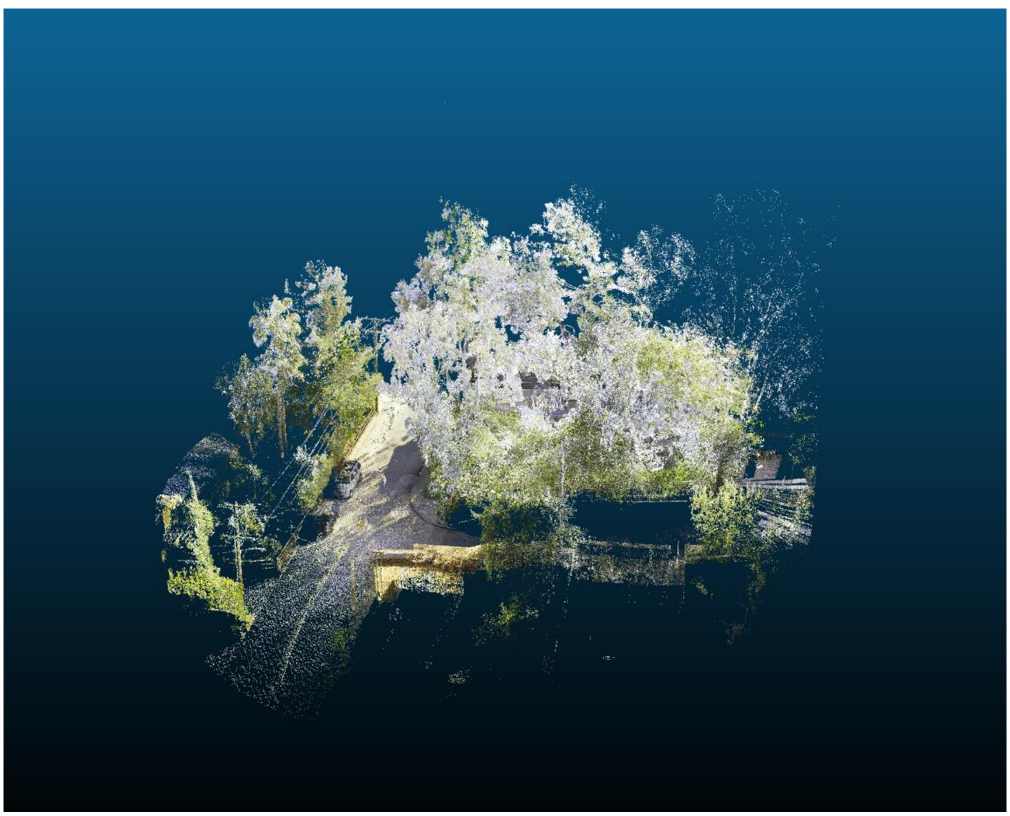


Figure 6-12: RTC 360 scanned outdoor environment at Reunion House

Overall, the smartphone scan is not suitable for generating site survey for Reunion House due to its limited range, difficulty in stitching scans together, susceptibility to interference from external factors, lack of accuracy, and inability to capture high-resolution data. Professional scanners are equipped with specialized sensors and can accurately capture large areas with greater accuracy. Aerial surveys can capture large areas with accuracy and details that are not possible with a smartphone scan. For these reasons, it is important to use more advanced LiDAR systems when creating site surveys for environments like Reunion House.

6.3 Monitoring

Building monitoring would track building changes over time. Professional LiDAR scanner can reach a 1/8" accuracy in this task; however, as discussed in 6.1, smartphone scans have larger deviation than 3/16" of inch, which cannot compete with professional scanner's accuracy. To further validating the quality of smartphone scanned data, a smartphone scan and a professional scanner scan was aligned in CloudCompare and computed a cloud to cloud distance, to observe area of deviation (methods were introduced in 4.3.2.). The result shows most smartphone scan points are in 0 - 0.25 meter (9 inches) from professional scanner points (Figure 6-13). Red marks deviation larger than 4 inches, which mostly occurs in blind area of smartphone scans. Green and blue represent deviation from 0 to 4 inches. Points in green are having larger deviation than points in blue, which more seen on corners and surfaces that laser shoot not perpendicular on. With most of the surface deviated from the ground truth scan, smartphone scans are not recommended for heritage conservation monitoring if professionals want to use it for seismic or detailed documentation because the error from scanning device and movement of building cannot be distinguished. As mentioned in 6.1 iPhone scans can document door panel thickness, location of small features, and angle of slopped surface. If these are purpose of monitoring, smartphone scans are recommended. As the scanning accuracy in smartphones improves, more types of measurements for monitoring will be possible. Although unlikely that very small dimensions will be captured, larger displacements, for example after a major earthquake, could be feasible.

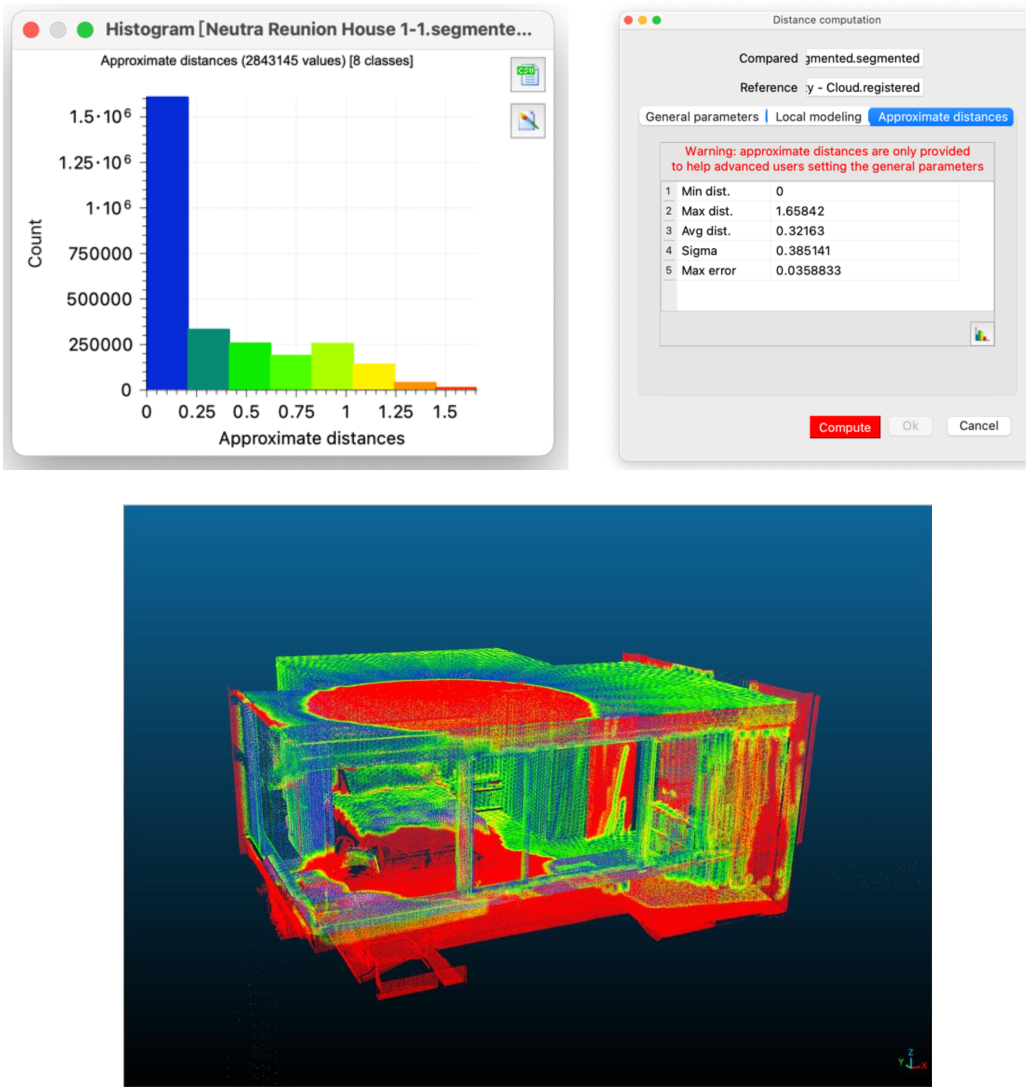


Figure 6-13: Cloud to cloud distance computation result in CloudCompare

6.4 Education

All scans can be used for digital virtual representation and the circulation of digital cultural reserves. The iOS application Matterport Capture was used in the case study at Reunion House. The result of scans can be edited on a smartphone app and uploaded to webpage for viewing. On the webpage, scans can be viewed from doll house view; measurements can be taken online, and virtual tours can be generated for free (Figure 6-14). A short video walk through and wide-angle photographs are downloadable from the webpage as well (Figure 6-15). With Matterport, technicians are having less control on the scans that Matterport processed it and only present the final product.

Figure 6-14: Doll house view of iPhone scanned Reunion House.

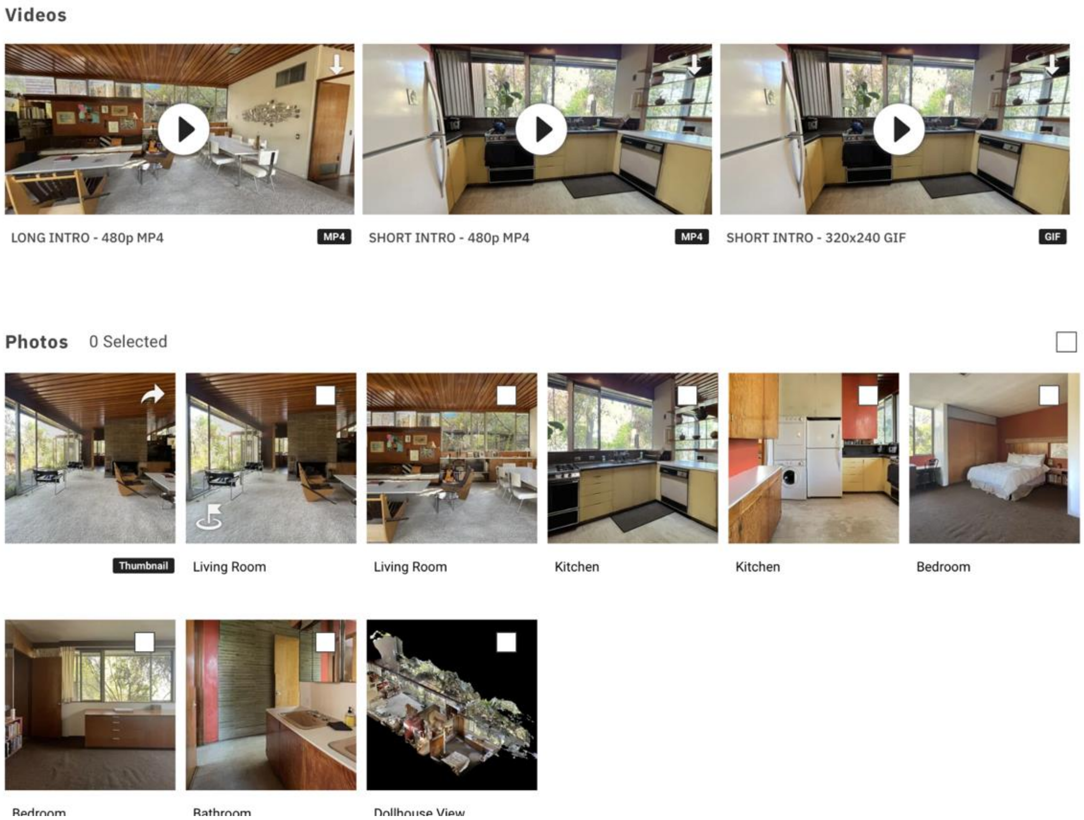


Figure 6-15: Downloadable Reunion House videos and photos from Matterport webpage.

Other deliverables are available with a cost, such as a schematic floor plan, a point cloud file, or a BIM file with Matterport scanners (Figure 6-16). According to WCAPT workshop, the quality of point clouds generated from Matterport scanner was still questionable in the professional field (White, 2023). Just like Matterport scanner acquired scans, iPhone scans can adjust privacy setting and share publicly. Except for a lower resolution on camera and unable for other deliverables, iPhone scans perform the same as Matterport scanners. Thus, considering cost-effective, time, effort, and ability to share and view universally iPhone scans are high recommended.

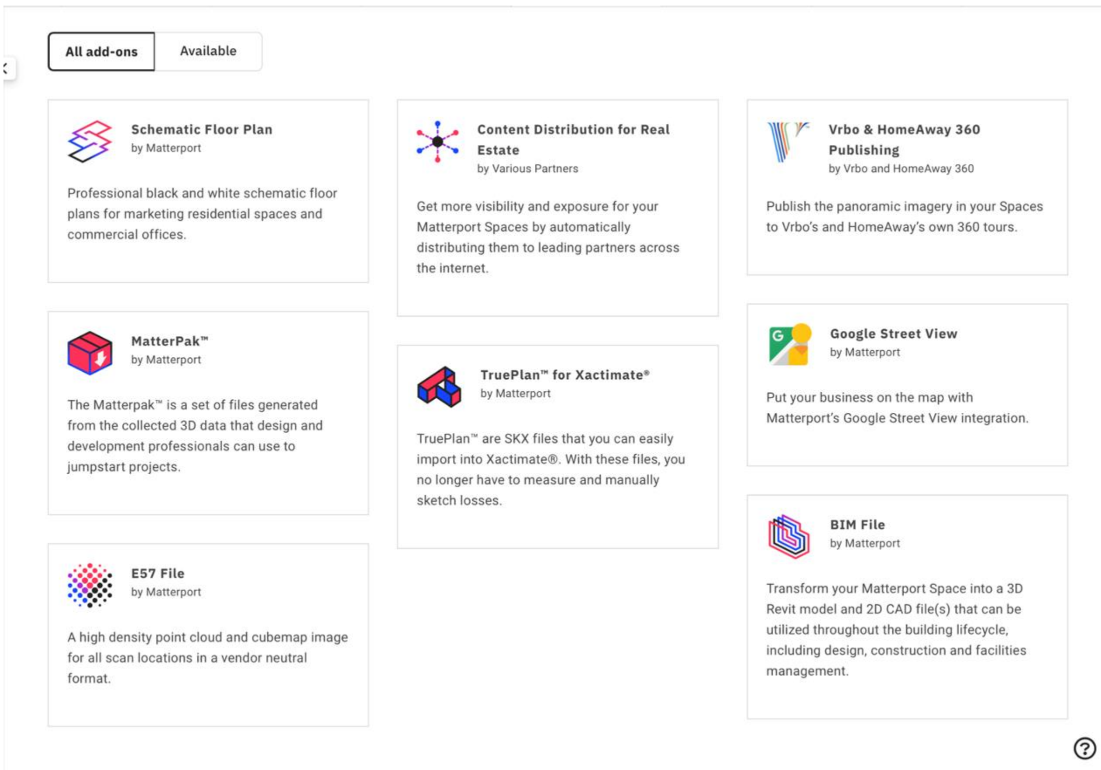


Figure 6-16: Other deliverables from Matterport webpage.

Although smartphone 3D scans may not meet the professional standards required for survey or documentation purposes, they can still be useful for education purposes. For example, they can be used to create 3D models of historical artifacts, buildings, or cultural heritage sites that can be viewed, manipulated, and studied by students or researchers. A low tolerance for accuracy may be acceptable in education settings, where the focus is on understanding the general form and structure of the environment, rather than capturing every detail precisely.

For educational purposes, however, a lower tolerance might be acceptable. Furthermore, smartphone 3D scanning can also be used as a tool for creative expression and experimentation. For instance, it can be used by artists or designers to quickly prototype or iterate ideas, or by hobbyists to create 3D models for interest. Therefore, while smartphone 3D scanning may have limitations, it still has a valuable role to play in education and other contexts.

6.5 Conclusion

Smartphone scans can be used for furniture size object in architecture scale 1/4”=1’-0” drawing for documentation, monitoring big changes, and for education purposes. iPhone acquisitions were not accurate enough for professional used in documenting rooms and window and door details in drawings. It also lacks the ability to capture site information with a high tree canopy and in large scale. Smartphone scans were also unable to be used in monitoring building movements in seismic monitoring. For these purposes, smartphone LiDAR cannot be substitute for professional scanners in heritage conservation uses.

While not suitable for certain heritage conservation purposes with current methodology, smartphone scans can be valuable in many cases. The current product of smartphone scan can be a useful tool for the documentation of endangered heritage. Heritage 3d scanning in war zones, unreachable sites by larger equipment, building at risk of immediate changes like those falling down to neglect, or unable to receive enough attention can be scanned with smartphone by any non-professionals, can still provide valuable information at lower accuracies than might be ideal. The instability of smartphone scans reduces their reliability for professional use, but they can be useful for quick documentation in case of endangered heritage and heritage at inaccessible locations. Further research is needed to address the errors caused by human decisions in the measuring procedure and to improve the methodology to make smartphone scans more accurate and reliable.

Smartphone scans can also be used in visual representation of heritage places in presentation to community discussion, stakeholders, and scholars if provided with supplemental numerical measurement. It can also be used to document the location of features with additional photograph or scan of details, which could be beneficial for heritage conservation professionals. The scan can be exported to virtual reality or augment reality devices, increasing the sense of a place, as well as providing universal access to heritage that have problems with Americans with Disabilities Act. Smartphone scans can also be used to create insurance record of heritage buildings.

Smartphone scanned point clouds can be manually aligned in AutoCAD. The visual process can increase deviation then impact measurement result. Furthermore, different from point clouds acquired from a professional scanner, which have a stable 1/8” thick points layer, smartphone scanned point clouds can be thicker and fuzzier. The irregularity in thickness and fuzziness can result mistake in human decision on tracing. It points to the possibility of directly measuring point to point distance from point clouds instead of tracing in computer aided drawing software. Considering built structures may shift or move over year, surfaces such as wall, ceiling, and floor can be angled or sloped. A lack of fixed referencing point on non-regular surface for measurements can cause different reading.

Further research should be done to exempt the possibilities mentioned above and determine acceptable error rates that might be different from the HABS standard.

Chapter 7 Conclusion

Chapter 7 discusses scanning heritage sites with smartphones and future work.

7.1 Scanning heritage sites with smartphones

The present research is focused on developing alternative scanning methods using portable devices for the purpose of serving conservation goals in the field of heritage conservation. 3D scanning technology plays a significant role in preserving the physical and geometrical aspects of both tangible and living heritages. The concept of utilizing smartphones for scanning was inspired by the realization that numerous heritage sites and buildings are not receiving adequate attention due to disparities in resources. These sites are often subject to factors such as lack of personnel, insufficient funding, operational barriers, or exclusion from legal or regulatory lists, which put them at a disadvantage. Therefore, more accessible scanning tools are required to aid those who are involved in conserving these invaluable cultural assets.

Conventional scanning and data processing methods typically require a high degree of proficiency in specialized equipment and software, which presents obstacles for individuals in the field of heritage conservation. The current study proposes to keep the technology accessible to anyone who wishes to scan, document, and share cultural assets that they consider valuable and significant. It is hoped that this approach will promote the protection of built environments that are physically inaccessible, endangered, or ignored.

It is important to emphasize that the use of smartphone scanning is not intended to replace professional scanned data. Instead, one can identify gaps and limitations in smartphone scanning to gain a better understanding of its potential applications in the field of heritage conservation and give a comprehensive analysis of the strengths and limitations of various professional scanners. Scanning has proven to be useful in diverse fields such as medication, industrial manufacturing, and ecosystem monitoring. In the context of heritage conservation, scans are instrumental in facilitating both digital and physical reconstruction of objects and sites, monitoring changes over time, evaluating structural states, and documenting for future research. Together with more traditional techniques such as tape measurements and photography, scanning provides a critical platform and foundation for researchers and stakeholders to undertake more effective measures in preserving buildings.

Digital documentation encompasses a range of media and methods, including 2D documentation, 360-degree photographs, and 3D documentation. Various scanning techniques have been categorized based on visualization format and data acquiring procedures. These include 2D documentation, encompassing measured drawings and film, as well as 3D photographs and 3D scanning utilizing various methods (Figures 7-1, 7-2). 2D scanning techniques commonly include photographs captured with film medium or panoramic photos, with cylindrical and spherical panoramic photos serving as a subcategorization. In contrast, 3D spatial data can be acquired through photogrammetry, structured light scan, triangulation scan, pulse scan, phase-comparison scan, as well as Matterport and 360-degree cameras. Each of these methods possesses its own strengths and weaknesses, and combining techniques thoughtfully can maximize benefits and achieve specific goals. With the recent release of iPhones equipped with built-in LiDAR sensors, the possibility of smartphone scanning assisting heritage conservation professionals in their work has emerged. However, limited attention has been paid to smartphone scanning in academia. Several journals have examined the accuracy of smartphone scanning, but this needs to be evaluated on a case-by-case basis. Further research is needed in this area, and to that end, permission has been obtained from the Neutra Institute to use the Reunion House at Silver Lake as a case study.

Figure 7-1: 360 degree photograph of Reunion House master bedroom.

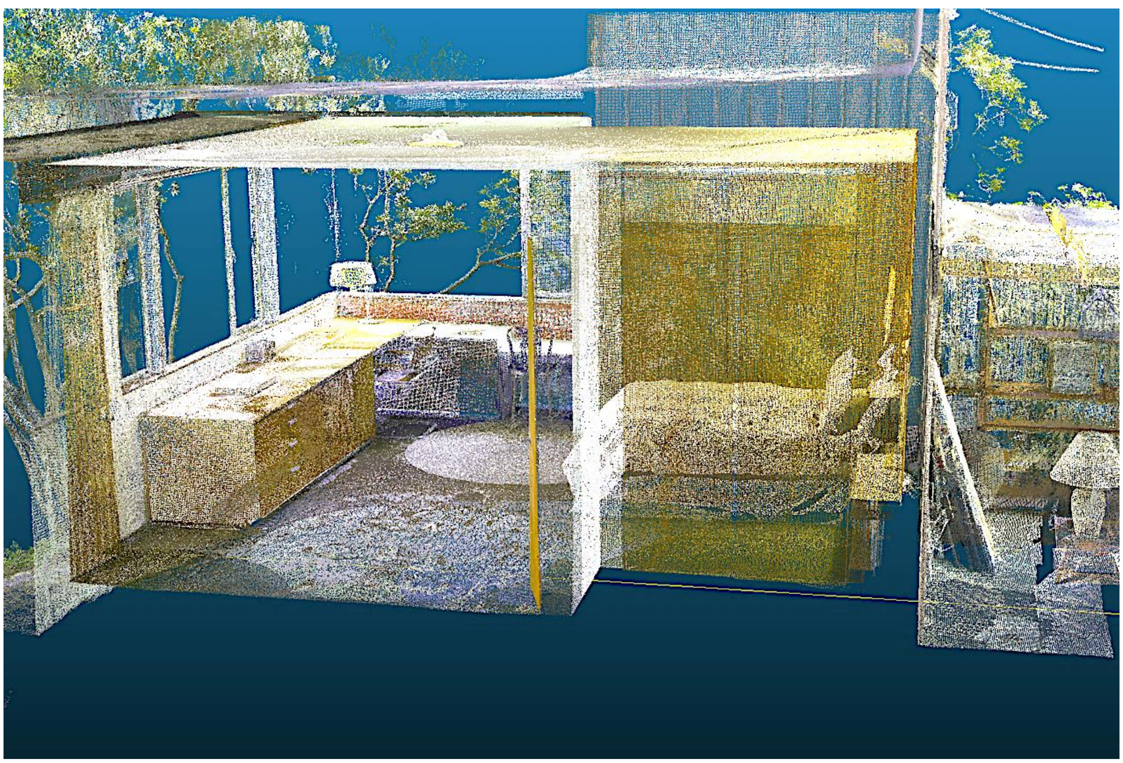


Figure 7-2: 3D scan of Reunion House master bedroom.

Richard Neutra is widely regarded as one of the most significant architects of the 20th century, renowned for his international style practice in the United States. The Reunion House at Silverlake, Los Angeles, represents a culmination of Neutra's signature architectural elements and was designed programmatically as a house featuring separate quarters for grandparents and grandchildren, along with a central meeting space (Lamprecht, 2021). This property is currently owned by the Neutra Institute for Survival Through Design, and was designated as a Historic-Cultural Monument by the City of Los Angeles in 2021.

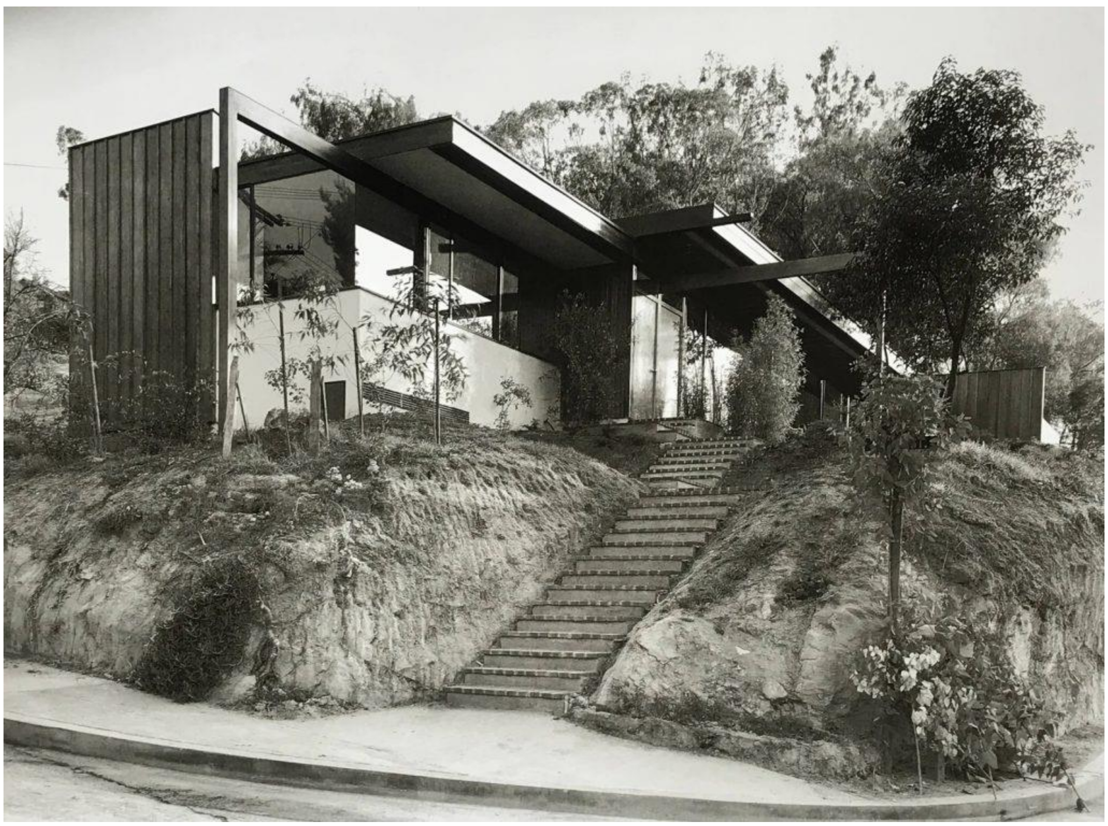


Figure 7-3: Historic photograph of Reunion House (University of Southern California, 1951)

A methodology for scanning heritage sites using a smartphone has been developed (Fig. 7-4). The study employed an iPhone 13 Pro and two smartphone apps, SiteScape and Matterport Capture, for data acquisition and processing. Four key heritage conservation tasks, namely site survey, documentation, monitoring, and education, were identified for validating the capability of smartphone scanning. The proposed methodology included the selection of appropriate software, data acquisition, data processing, comparison to traditional methods, and a case study involving professional scanners. By following this methodology, one can utilize a smartphone and select suitable software to scan a heritage site in order to achieve heritage conservation goals. SiteScape and Matterport smartphone apps were chosen due to their exceptional ability to fulfill the research objectives. SiteScape was designed for use in data acquisition processes such as surveying, documenting, and monitoring. The desktop software CloudCompare was be utilized for registering multiple scans, thereby enhancing accuracy and precision. Furthermore, smartphone-scanned data was compared to traditional methods and professional scanner-scanned data. Matterport was selected for the purpose of its potential for educational uses. The data acquisition, processing, and visualization achieved through Matterport were compared to traditional methods and a high-end scanner.

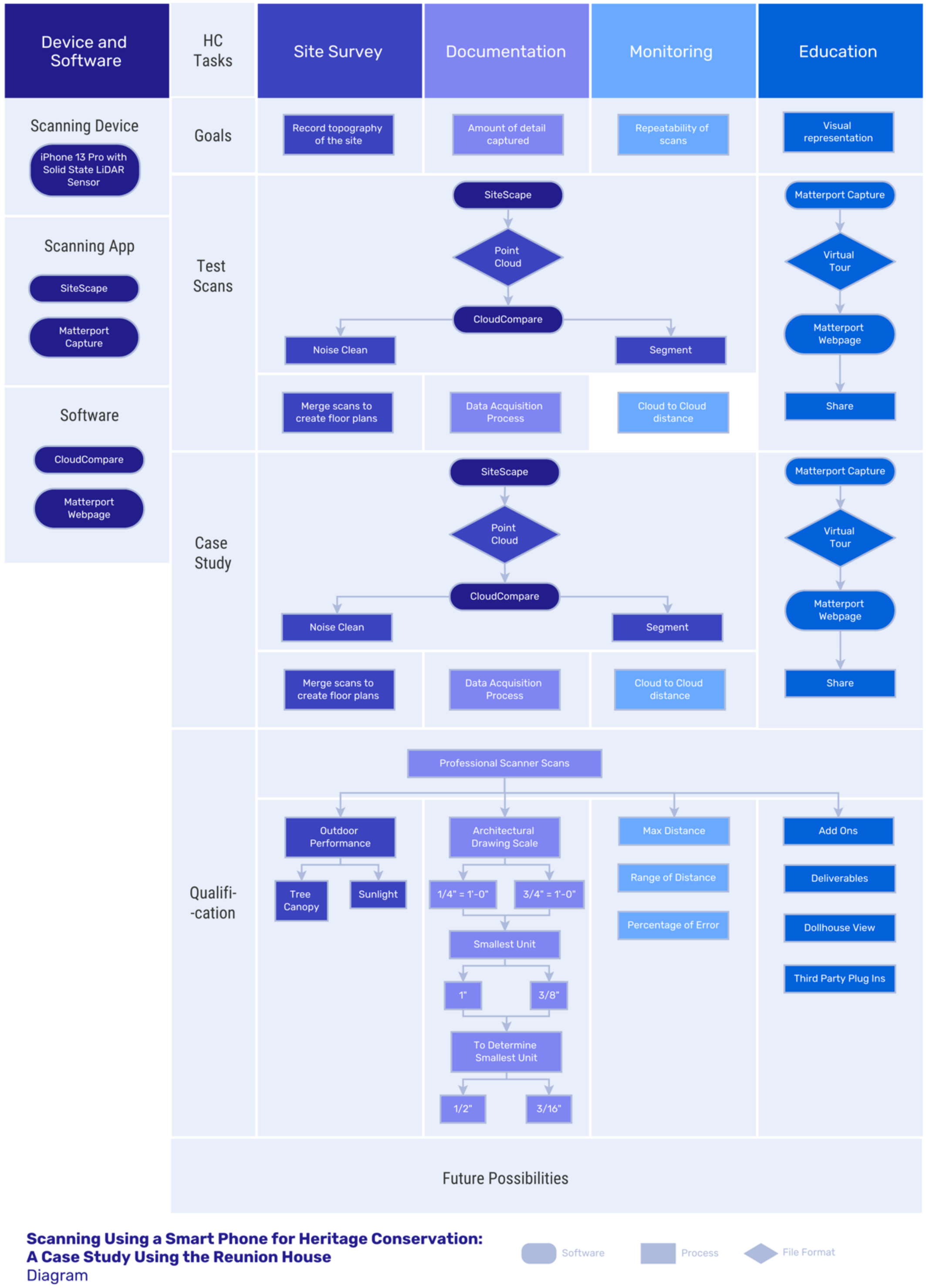


Figure 3-1 Proposed methodology

Test scans were conducted at the Hoose Library of Philosophy in Mudd Hall, USC campus (Figure 7-4). A detailed start up guide was written as instructions for heritage conservation professionals. The start-up guide describes the process of scanning the interior of a space using SiteScape and merging multiple scans to generate a floor plan. It also outlines the process of scanning the same area with different point density parameters (low, medium, and high) using SiteScape. Two of the three scans were used to investigate the possibility of overlaying scans to increase accuracy. It introduced the process of acquiring geometric data of the same area using SiteScape with the same parameter. CloudCompare was utilized to compute the distance between the two exact scans (scan 3 and scan 4) to examine the repeatability of smartphone-scanned data. The last part of the startup guide demonstrated Matterport Capture for iPhone and a tripod to take 360-degree photographs to generate a virtual tour that can be shared through links on a website.

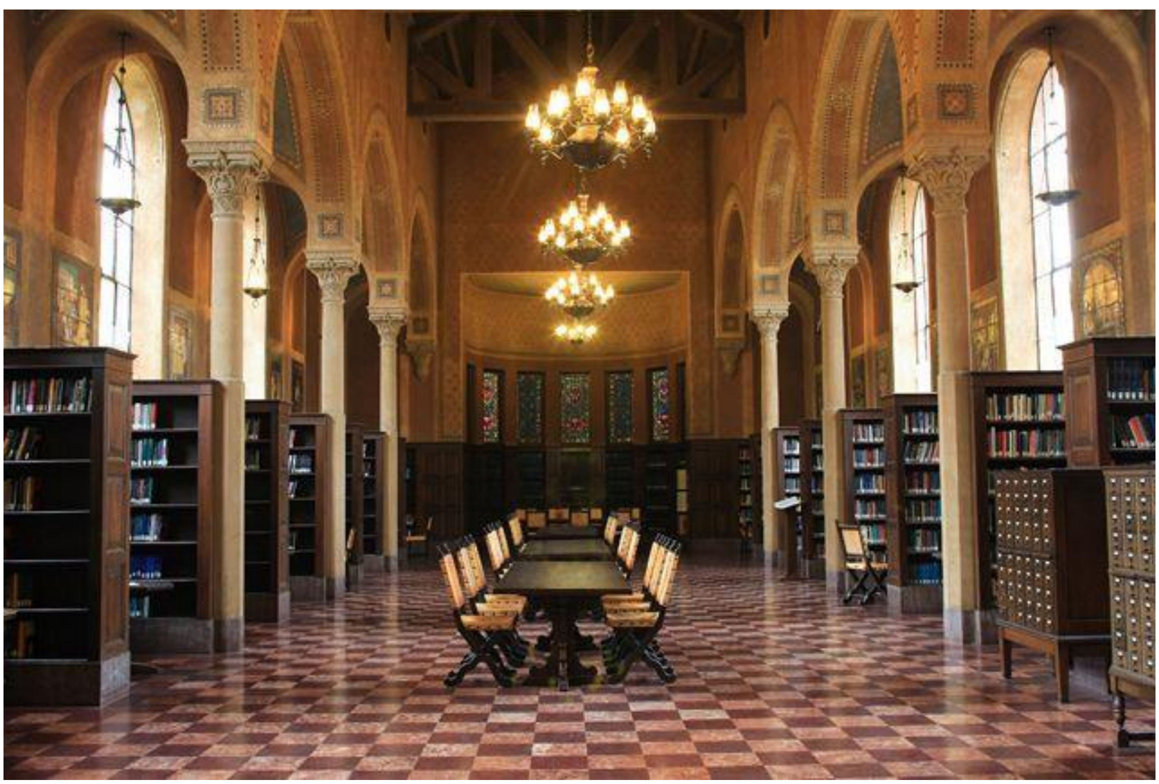


Figure 7-4: Hoose Library of Philosophy at Mudd Hall, USC.

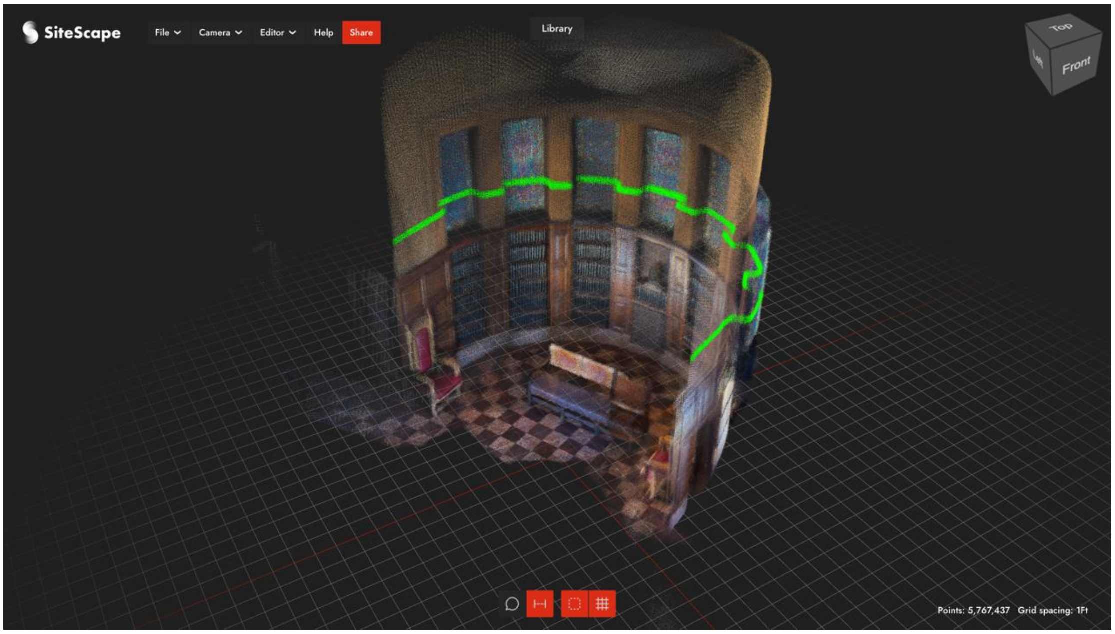


Figure 7-5: Point cloud scan of Hoose Library of Philosophy.

The results from the test scans demonstrated the relative simplicity of all four methodologies. The floor plan generated in the first methodology could be used for site survey purposes and a comparison of this floor plan with scanner-scanned data may offer valuable insights (Figure 7-6). The second methodology shows that overlapping two scans can increase the points describing the same surface, but a thicker layer of points may not contribute to documentation due to increased error (Table 7-1). For monitoring purposes, the third methodology shows that smartphone-scanned data cannot produce repetitive data every time unless more stable scanning methods or better alignment computation is employed (Figure 7-7).

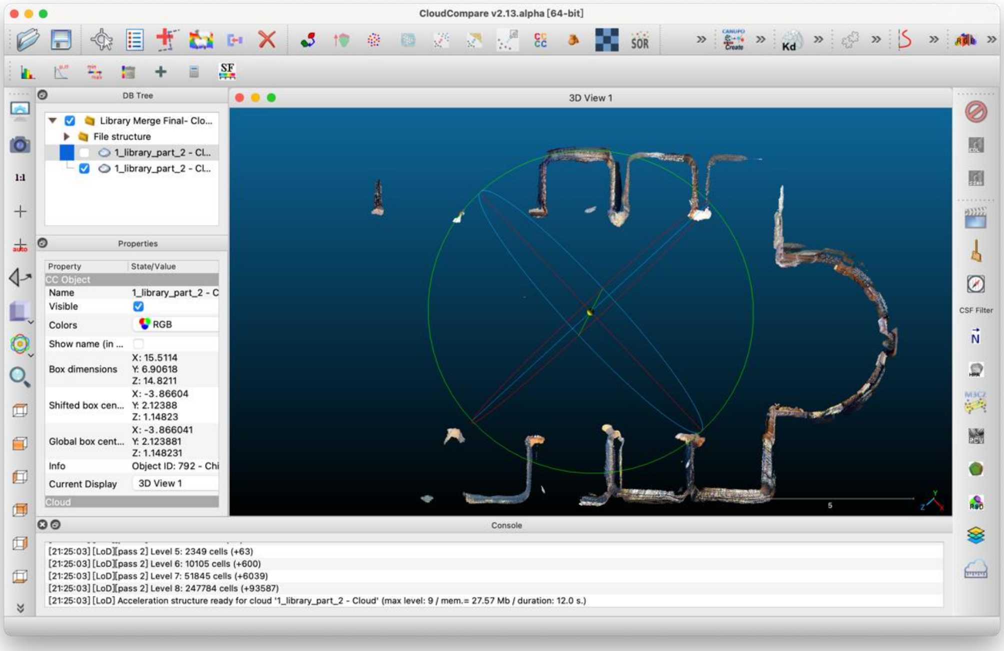


Figure 7-6: Merged scan of Hoose Library of Philosophy at Mudd Hall through CloudCompare.

Table 7-1: Result in number of total points from point cloud from overlapping.

Scans	**Number of Points**	**Point Cleared**
Scan 1 Filter	2,764,678	
Scan 1	3,550,490	785,812
Scan 2 Filter	5,540,899	
Scan 2	5,768,038	227,139
Scan 1+2 Merge	9,318,528	
Scan 1+2 Filter-Crop-Merge	8,305,577	1,012,951
Scan 1+2 Merge-Filter-Crop	7,091,553	2,226,975

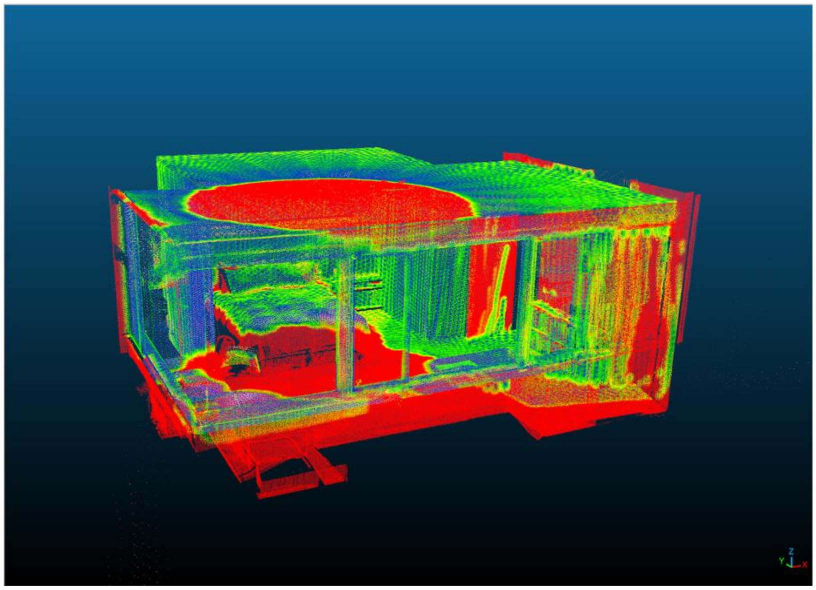


Figure 7-7: Cloud to cloud distance computation result in CloudCompare

The study conducted at Reunion House involved a comparison of smartphone scans and professional scans in the master bedroom. Both sets of scans were imported into AutoCAD, and their respective dimensions were compared, following which a range of errors was computed. The comparison results were subsequently compiled in a tabular format, and recommendations were provided based on the outcomes of the analysis. The scale and standard of accuracy are important when generating drawings and models for heritage conservation. Architectural scales, such as 1/4”=1’-0” and 3/4”=1’-0”, are commonly used to document features of similar scale, with the smallest unit being 1” and 3/8”, respectively. To evaluate the performance of smartphone scans in creating as-built drawings on paper, scales of 1/4”=1’-0” and 3/4”=1’-0” with the smallest units of 1/2” or 3/16” will be used as a standard. For digital documentation, a standard accuracy of 1/8” is required for tracing three-dimensional models, floor plans, or section drawings. The most common scale used for engineering drawings and maps is 1”=20’, with the smallest unit being 0.4’. To determine 0.4’ in a map, a factor of two than the smallest feature, which is 0.2’ (2 2/5”), is needed.

A final comparison was to tests the accuracy of smartphone scanned data acquired on a tripod to professional scanner scanned data (Figure 7-5). The smartphone scans are limited by the angle of the LiDAR sensor, resulting in blind areas on the ceiling and floor. Tilting the smartphone up or down can reduce the blind areas. The scans were manually aligned with professional scanner captured point clouds, and measurements were taken using tracing and the linear dimension tool. The thickness and fuzziness of points in the iPhone scans varied based on different point density, distance, and captured angle, making tracing and measurement difficult. Room dimensions were measured individually in all eight scans through the plans and sections, but the width of one room could not be measured due to missing data.

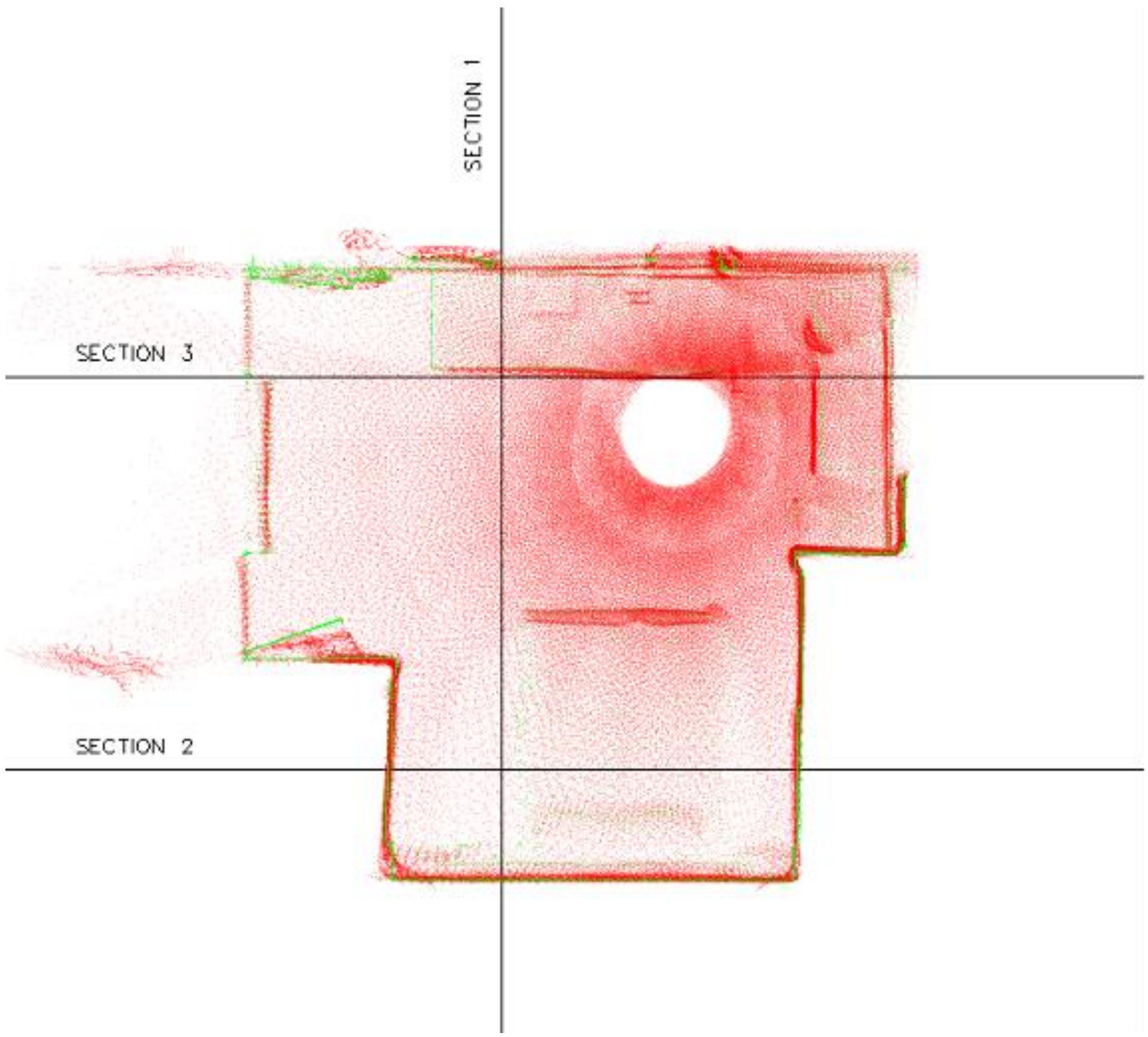


Figure 7-5: Overlapping professional scanner point cloud with iPhone scanned point cloud.

Three section views were created to compare the deviations and differences between the two devices. Through visual comparison, smartphone scans can capture details such as the thickness of sliding doors, slop of roof, and location of features.

Potential errors arising from human interpretation can occur during the manual alignment process, different measurement setpoints on angled surfaces such as walls, ceiling, and floor, and distinguishing fuzzy points from the captured surface in point clouds. In order to assess the accuracy of the scans, sections were created to measure room dimensions, and the percentage of error of each target was calculated.

Smartphone scans on furniture scale met the architectural drawing standard and can be used for heritage conservation purposes. However, for room or building scale, the quality of data was questionable with deviation exceeding 1/2 of the smallest unit needed for heritage conservation tasks. The use of low point density mode was found to achieve a better result with a smaller rate of error, with raw data performing better than merged files. Overall, the findings suggest that while smartphone scans may be suitable for heritage conservation tasks, there are limitations to their accuracy and reliability, and further improvements in methodology are necessary to improve their effectiveness for professional use.

Qualifications of heritage conservation tasks including site survey, documentation, monitoring, and education were made (Figure 7-). Smartphone scans are not a suitable option for site surveys due to limitations imposed by the vegetation canopy and lighting conditions, which necessitate excessive merging of scans. However, the high point density mode of smartphone scanning is deemed appropriate for horizontal acquisition in documentation, particularly at a scale of 3/4"=1'-0". In contrast, it is not recommended for the documentation of room sizes, as it is unable to capture details accurately. Furthermore, smartphone scanning is not recommended for monitoring building shifts, as the deviation is too large to distinguish between scanning errors and actual building movement. Despite these limitations, smartphone scanning can be useful for educational purposes, as it can yield results similar to those obtained from professional scanners such as Matterport. Furthermore, the strengths of smartphone scanning include its cost-effectiveness, ease of use, and universal shareability. However, these applications must be approached with caution, as the limitations of smartphone scanning can lead to errors and inaccuracies.

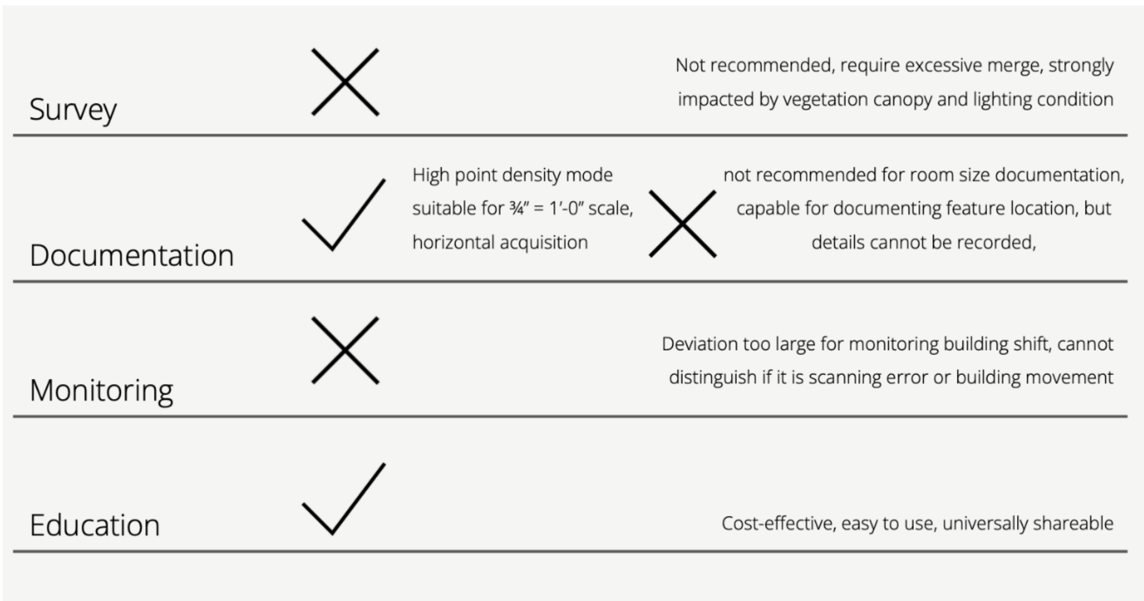


Figure 7-6: Qualification of smartphone scan for heritage conservation tasks.

7.2 Future work

Although the goal of proposing a methodology of conducting scans with smartphones for heritage conservation was accomplished, there are several improvements that could be done in order to achieve better results.

7.2.1 Improvements

Many adaptations, tests, and experiments that could have been beneficial were left for future studies due to a lack of time. These include increasing scan features and trials in the case study to produce an additional list of products from smartphone scanning, which can potentially lead to a better representation of heritage resources. Larger-scale heritage sits can also be merged with supplemental point clouds acquired from smartphones. Moreover, the potential of the point cloud data can be further investigated for other heritage conservation purposes. Smartphone scanned data can be computed in different software using greater variety of tools in evaluating quality and qualifications. Scans obtained from different devices, techniques, and software such as Android, photogrammetry, and Polycam can be compared with the existing data to provide a more comprehensive understanding of the capability of the smartphone as a portable and affordable scanning device for heritage conservation professionals. With more time, improvements can be done by implementing smartphone-captured data into game engines to simulate experiences in virtual environments with augmented reality and virtual reality (Figures 7-7, 7-8). Furthermore, the scanned point cloud can be computed into a mesh and 3D printed on different scales, exhibited at different locations, or mass-produced. This would help to increase the level of understanding of heritage sites and also could create a sense of connection with the history.

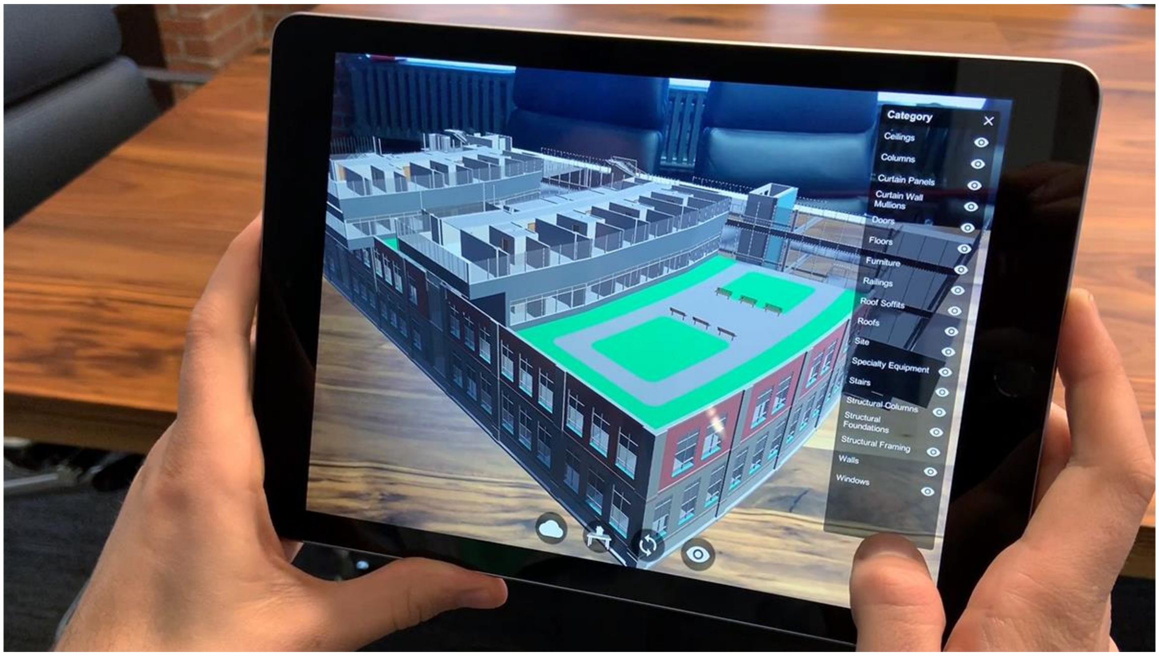


Figure 7-7: Game engine used in architecture (The Architect's Newspaper, 2019)

Figure 7-8: Virtual reality in architecture (Parametric Architecture, 2022)

For the purpose of benefiting heritage conservation professionals with accessible tools, improvements in the clarity and details of the *getting start guide* (Chapter 4) can be helpful. The guide can also be filmed as a video to engage with diverse audiences. Publishing the guide together with the research outcome in journals and online will make smartphone scans available for broader heritage conservation professionals. Presenting at conferences and workshops will have a similar positive effect. The use of smartphones as a tool to obtain data offers the potential to expand the accessibility of heritage to the public, making heritage more accessible, interesting, and engaging. Online platforms such as Sketchfab allow users to publish and share 3D content; if the methodology can be widely adopted, the point clouds should be uploaded and published.

7.2.2 Other topic areas

There are other areas in heritage conservation that could benefit from the use of the smartphone. Heritage conservation is a broad field that involves various tasks beyond the areas considered: site survey, documentation, monitoring, and education (Figure 7-9). Although the proposed tasks are crucial, heritage conservation encompasses many other purposes that are equally essential. Smartphone capabilities in the field can be explored more extensively to aid in the conservation of heritage.

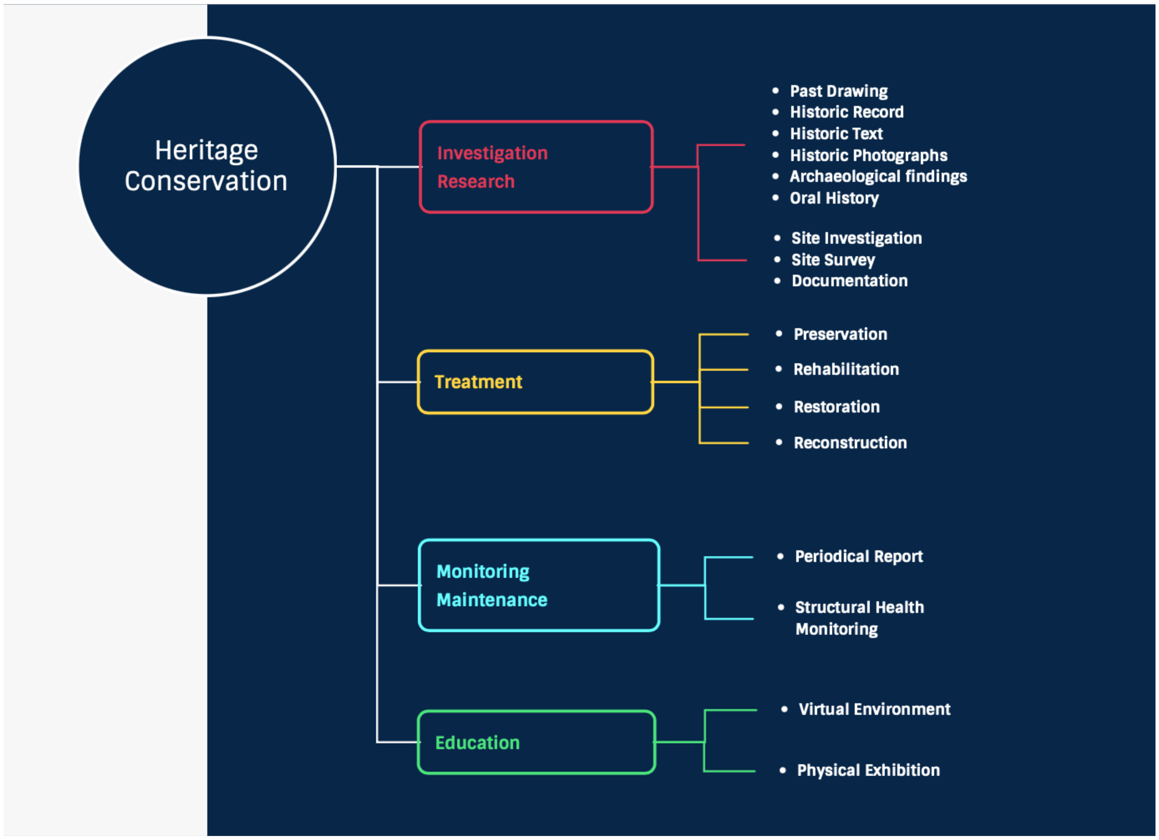


Figure 7-9: Heritage conservation task diagram.

Not all smartphones have a LiDAR sensor, which is an essential tool for creating 3D models of objects or structures. However, there are many other ways a smartphone can assist heritage conservation professionals in reducing costs. For example, the camera function of a smartphone can be used to capture images of objects or structures that need to be conserved or restored in creating records. These images can then be used for reference purposes during the conservation process. Moreover, the recording function on a smartphone can be used to capture audio recordings of interviews with experts or oral histories related to heritage objects or structures in documenting oral history. This information can then be used to understand the cultural significance of the object or structure and inform the conservation process. Smartphone applications such as Fulcrum help create an architecture description in an organized way. With smartphones, text or audio information can be scanned through a QR code and delivered to an audience in exhibitions. Translate audio to text, document scan, and GPS system on smartphone can all benefit cultural heritage protection and documentation.

Additionally, there are various apps and software available on smartphones that can aid heritage conservation professionals in their work. For example, there are apps that can be used to measure distances and angles accurately, which can be helpful in creating precise 3D models of objects or structures. The built-in functions of a smartphone can be beneficial for preliminary jobs in heritage conservation tasks, and more research can be done in this area. Although not all smartphones have the same capabilities, there are still many ways that a smartphone can assist heritage conservation professionals in reducing costs and making their work more efficient. The current capabilities of smartphone LiDAR are still limited, and the accuracy and resolution of scans can vary widely. If smartphone LiDAR technology were to improve, it could greatly enhance the possibility of using smartphones for heritage conservation, making it easier to document and preserve historic sites and artifacts.

Additionally, more research on photogrammetry, which is another technique used to create 3D models, could also lead to further advancements in smartphone scanning for heritage conservation. By combining these technologies and improving their capabilities, the potential for preserving cultural heritage could be greatly increased. Therefore, exploring the capabilities of smartphones in the field of heritage conservation can lead to new and innovative ways to preserve our cultural heritage.

7.2.3 Future work

During the research, obstacles appeared in the alignment and distance computing of smartphone-scanned point clouds. Without improvements in the algorithm of alignment and true distance computing from CloudCompare, the accuracy of data cannot be validated. Future work can be done to either improve the algorithm or use another software to process the data. More research and tests should be done to structures and sites with various scales. With the collective data, benchmarks and metrics can be produced for scanning with smartphones. A multiplicity of supported equipment such as drones should also be implemented in future works for sites or structures that cannot be easily accessed. The limits and strength of smartphones as 3D scanning devices for heritage conservation should also be tested in endangered or hostile environments.

With cost-effectiveness being a concern for certain projects, alternative low-cost scanning solutions such as photogrammetry and structure from motion should be considered. Results from different cost-effective documentation methodologies should be compared. The potential of smartphones in heritage conservation should be expanded too. The acoustics of structures has been studied by scholars; based on the research, smartphone application in identifying acoustic differences among heritage sites can be developed. The public can learn the structure from a different perspective. The application can also create a more equitable environment for people with vision disabilities. 3d scanning with 3d printing could also be done.

7.3 Summary

The use of a smartphone allows for accessibility and affordability of 3D scanning to heritage conservation professions over that provided by more expensive professional solutions. However, it is not the only issue to face. HABS determined digital technologies are more suitable as tools for generating documentation of structures than the final product because the frequently updated software and hardware cause data migration and archival issues. The future of point clouds acquired in the past decades should be a concern. The possibility of an official file format that can be shared universally and stored locally with a small file size for decades should be considered in future research. With different researchers and organizations producing results of varying quality, the 3D scanning process is often inconsistent.

Developing standards for the amount and quality of data to be collected is necessary to ensure that the data being collected is consistently high quality and can be used for accurate comparison and analysis.

Point clouds can be traced in computer-aided modeling and drawing software, which eventually required decision-making to translate the point clouds into a product. If in the future 3D scanned data can be the format for the architecture, engineering, and construction industry, the deviation can be further reduced, and accuracy can increase. In the unforeseen future, point clouds may replace modeling from software such as Revit and Rhino; materials and properties can be directly assigned to the cluster of points. There are current software and websites generating 2D drawings directly from point clouds, nevertheless, the algorithm cannot process certain complicated geometry. The advancement can also be a direction for future research.

Another area of future research is the use of smartphone scanning to evaluate the emotional impact of heritage sites. By creating 3D models of heritage sites, researchers can analyze the physical features that contribute to a sense of place and feelings. This information can be used to identify ways to enhance the emotional impact of heritage sites and create more meaningful experiences for visitors. Social media applications might be able to combine several of the afore-mentioned techniques As the technology on smartphones improves, heritage conservationists have more opportunities towards augmenting their existing toolset.

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Appendix A

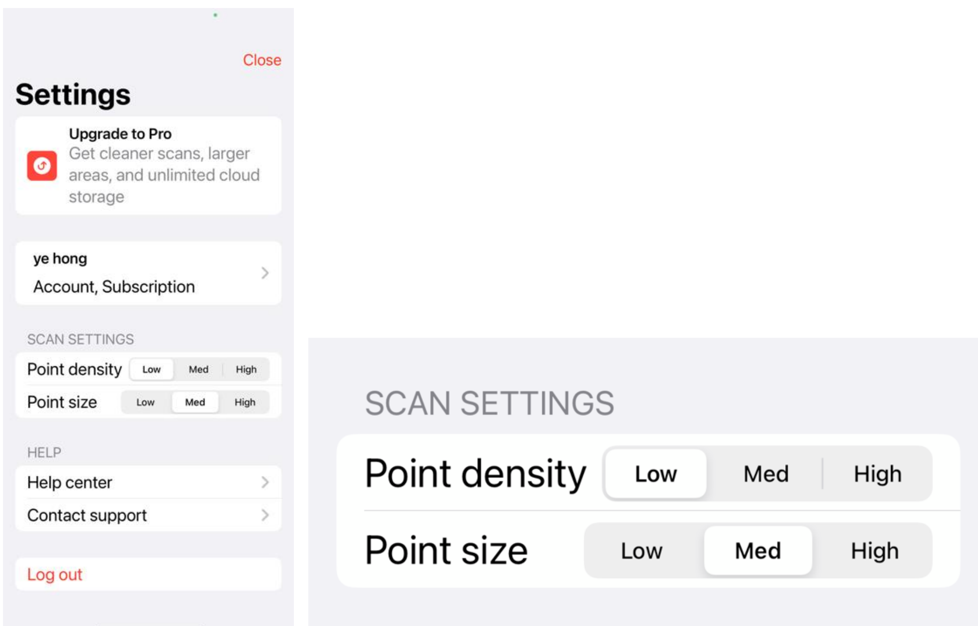
Data Acquisition for Test Scan Comparison

Three scans will be acquired by the same smartphone application SiteScape with low, medium, and high point density. Three different point density scans were processed to examine if overlapping will help increase points density and precision in describing scanning target.

Scan 1 (Low point density)

I. Preparation

a) Repeat 4.1.1 I. Preparation, set point density to Low and point size Low (Figures B-1, B-2)



Figures B-1 and B-2: *Scan 1* point density parameters

II. Data Acquisition

a) Repeat 4.1.1 II. Data Acquisition with method A or B

III. Save and Export

a) Repeat 4.1.1 III. Save and Export as *scan 1*

Scan 2 (Medium point density)

I. Preparation

a) Repeat 4.1.1 I. Preparation, set point density to Med and point size Low (Figure B-3, B-4)

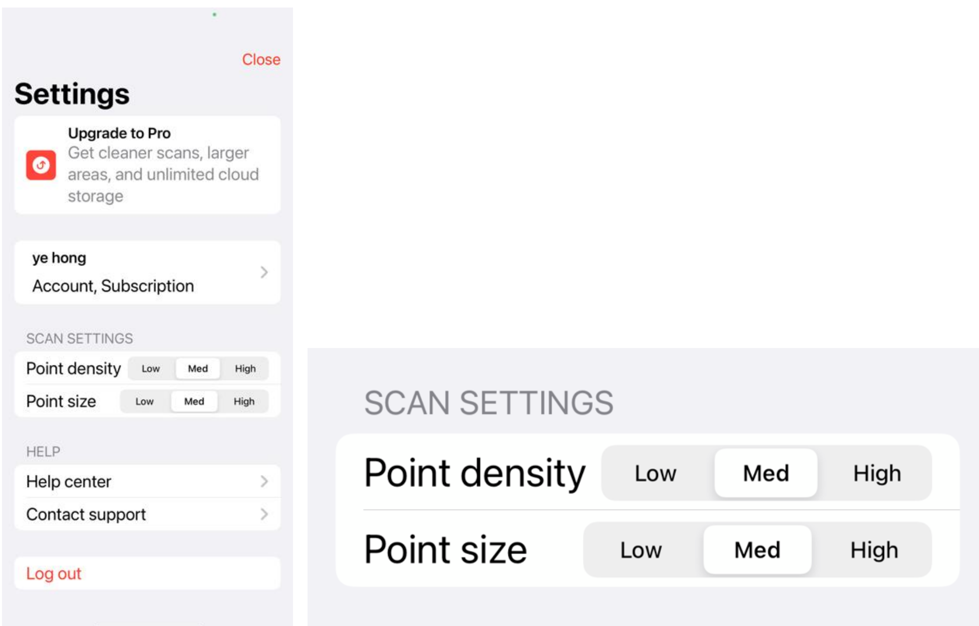


Figure B-3 andB-4: *Scan 2* point density parameters

II. Data Acquisition

a) Repeat 4.1.1 II. Data Acquisition with method A or B

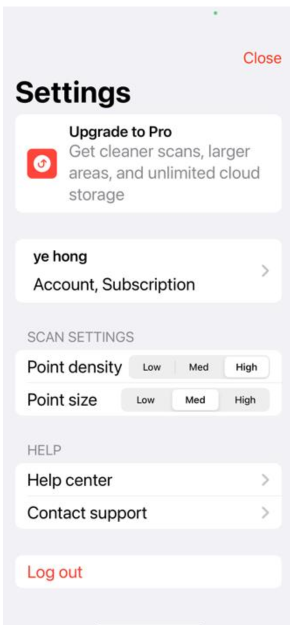
III. Save and Export

a) Repeat 4.1.1 III. Save and Export as *scan 2*

Scan 3 (High point density)

I. Preparation

a) Repeat 4.1.1 I. Preparation, set point density to High and point size Low (Figure B-5, B-6)



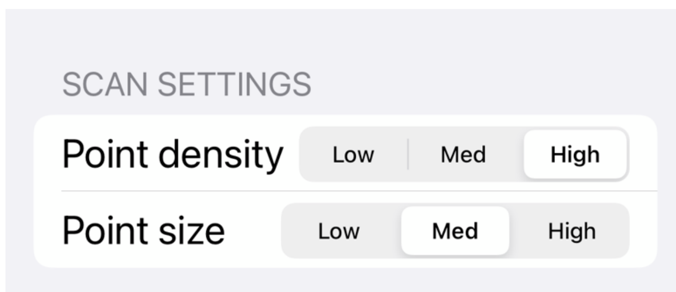


Figure B-5 and B-6: *Scan 3* point density parameters

II. Data Acquisition

a) Repeat 4.1.1 II. Data Acquisition with method A or B

III. Save and Export

a) Repeat 4.1.1 III. Save and Export *scan 3*

Data Processing

The post-acquisition process includes synchronizing to cloud and downloading from SiteScape webpage.

With the raw scanning data, *scan 1* (low point density) and *scan 2* (medium point density) were selected for following examination on the overlapping process proposed in Chapter 3. Scan 3 (high point density) results in overly thick points on surfaces, which will impact alignment and comparison. To increasing the points describing objects, a methodology of overlapping *scan 1* and *2* into one 3D space was proposed. *Scan 1* and *scan 2* were noise cleared and cropped as steps mentioned in 4.1.2.

Following the methodology proposed in Chapter 3, comparison set 1overlapped processed data of *scan 1* and *scan 2* together; comparison set 2 overlapped raw data of *scan 1* and *scan 2*, then cleared noise and cropped (Figure B-7).

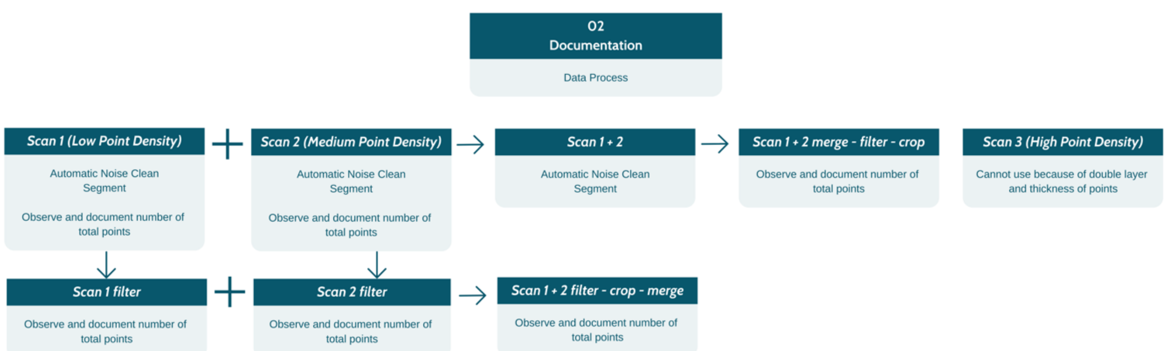


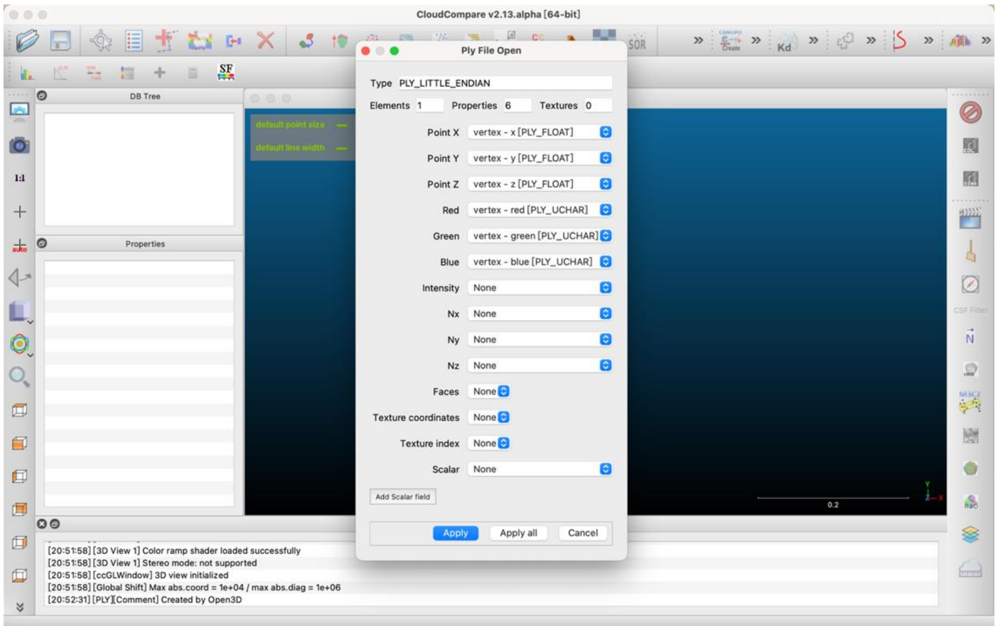
Figure B-7: Documentation data process workflow

I. Download File

Data acquired from smartphone for the purpose of heritage conservation documentation should be downloaded and ready for computer processing.

a) Download scanned data in PLY file format to computer; then open CloudCompare.

b) Click File-Open, change file format to PLY mesh, select the scan file, and open in CloudCompare. By this step, the scanned data should be able to view in CloudCompare in point clouds (Figures 4-77).



Figures B-8: Open file in CloudCompare

c) Observe and document the number of points from properties window for all three scans (Figures B-9, B-10).

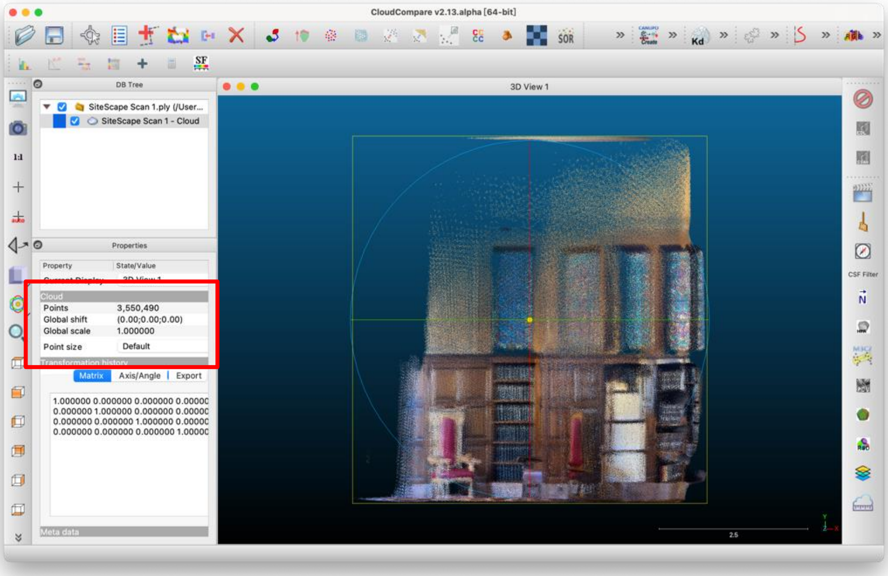


Figure B-9: Number of points for *scan 1*

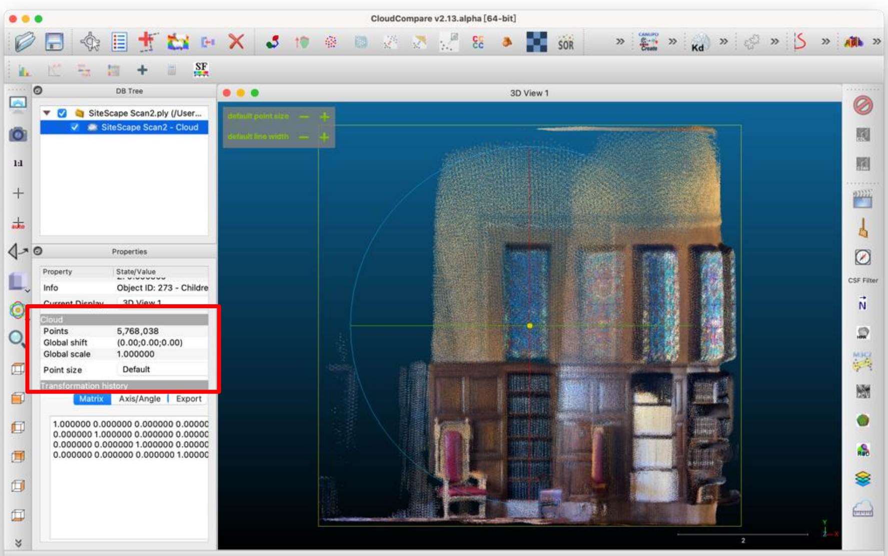


Figure B-10: Number of points for *scan 2*

II. Data Preparation

To improve raw data's operability in examining the ability of smartphone scanned data, scans should be automatic noise cleaned and cropped.

a) Automatic noise clean and crop both *scans 1* and *2* following the 4.1.1 instruction.

b) Observe and document the number of points from properties window for *scan 1*, *scan 1 filter*, *scan 2*, *scan 2 filter* (Figures B-11, B-12).

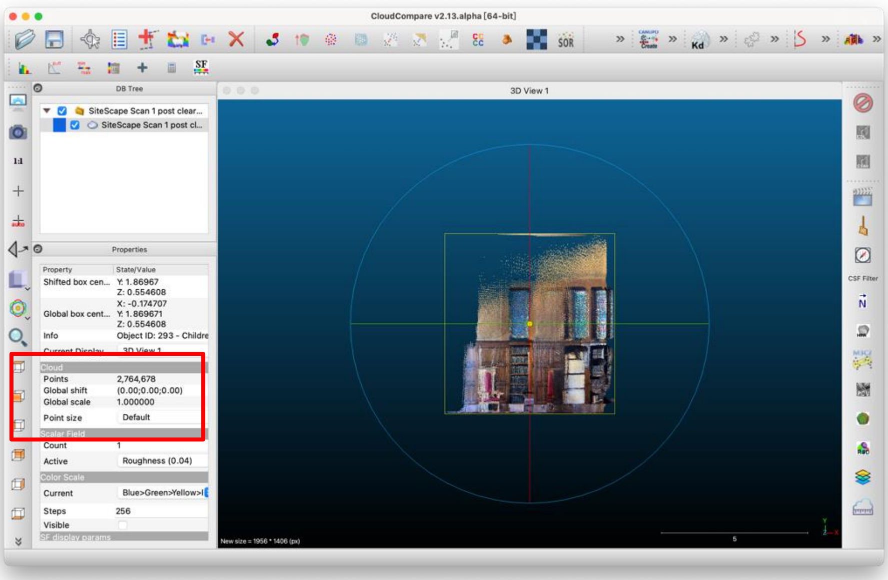


Figure B-11: Number of points of *scan 1 filter*

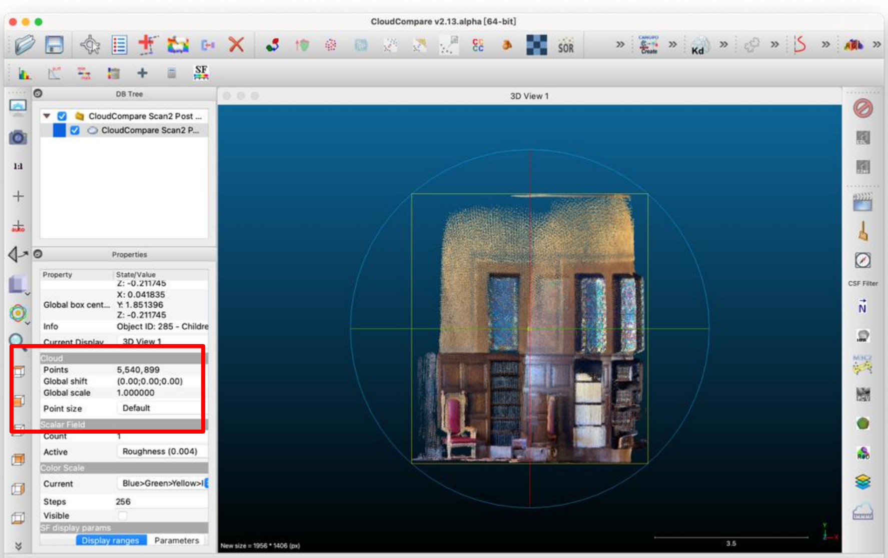


Figure B-12: Number of points for *scan 2 filter*

c) Save *scan 1 filter* and *scan 2 filter* as individual files

3. Data Comparison

Processed scans are ready for comparison. The purpose of the comparisons is to understand how overlapping impact smartphone scanned data's quality.

a) Open a new CloudCompare window; import *scan 1* and *scan 2* in one file.

b) Automatic noise clean and cropping the combined file following instructions from 4.1.1

c) Save the file as *scan 1+2 merge-filter-crop*, observe and document the number of points from the properties window (Figure B-13).

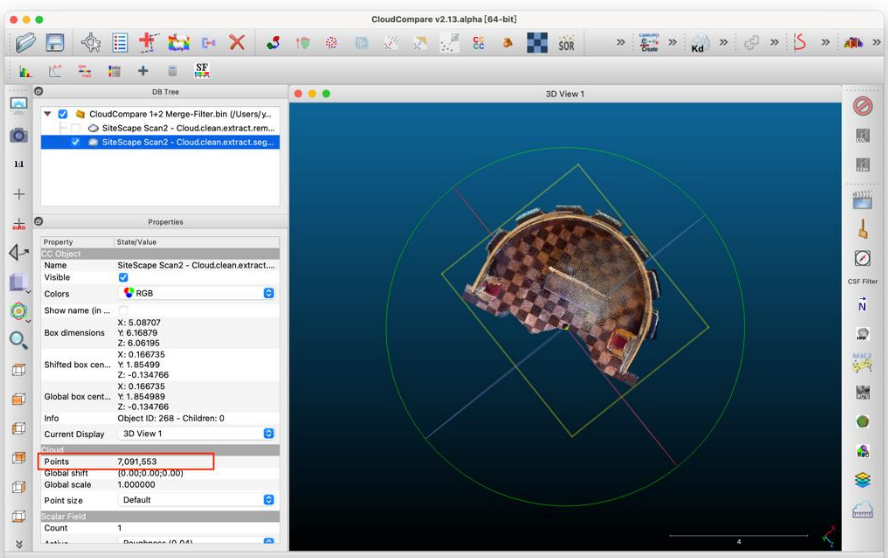


Figure B-13: Number of points of *scan 1+2 merge-filter-crop*

d) Open a new CloudCompare window, import scan *1 filter* and scan *2 filter* in the same file.

e) Save file as *scan 1+2 filter-crop-merge*, observe and document the number of points from properties window (Figure B-14).

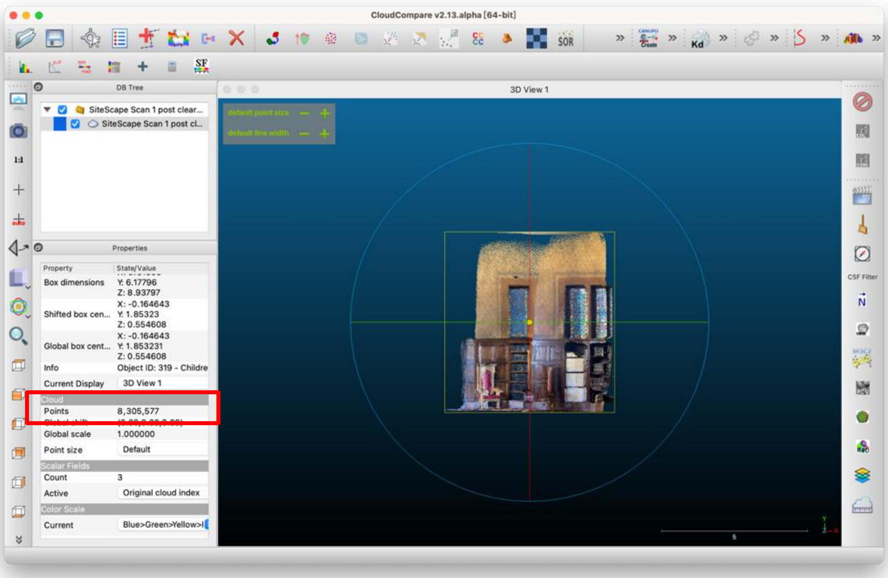


Figure B-14: Number of points of *scan 1+2 merge-filter-crop*

f) Compare the change in the number of points to see if overlapping point clouds would increase the number describing the same target, as well as if the number of total point number is the sum of two scans. If two points can be overlapped and the number of total point increase, more points are describing the same surface.

The number of points as scanning results are different for different point densities (Table B-1)

Table B-1 SiteScape test scan number of points

Test Scan Number	Parameters (Point Density)	Scan Method	Points Obtained
Scan 1	Low	Handheld	3,550,490
Scan 2	Medium	Handheld	5,768,038

The number of points in raw and processed files are smaller for each scan (Table B-2)

Table B-2 Results of data processing for HC documentation

Scans	**Number of Points**	**Point Cleared**
Scan 1 Filter	2,764,678	785,812
Scan 1	3,550,490	
Scan 2 Filter	5,540,899	227,139
Scan 2	5,768,038	
Scan 1+2 Merge	9,318,528	
Scan 1+2 Filter-Crop-Merge	8,305,577	1,012,951
Scan 1+2 Merge-Filter-Crop	7,091,553	2,226,975

Results in table 4-2 reviewed that registering two or more point clouds together can increase the number of points describing the object. The number of points for overlapped point clouds are the sum of the two individual files. *Scan 1* merge with *scan 2* had 3,550,490 (*scan 1*) pulsed 5,768,038 (*scan 2*), resulted in 9,318,528 points in file *scan 1+2*. *Scan 1+2 filter-crop-merge* 8,305,577 points which was 5,540,899 (*scan 1 filter*) +2,764,678 (*scan 2 filter*). However, merging two point clouds can increase both the number of points describing the object, and error points. It was partially proved by the difference in number of points resulted from different process order that *Scan 1+2 Merge-Filter-Crop* had a smaller number than *Scan 1+2 Filter-Crop-Merge*. The result showed filtering a combined file can take out more fussy points than combining the two filtered files. These increased number on erased points indicate more noise points can be identified than only add up the number of noise point from individual files. With more noise cleared from the combined file, *Scan 1+2 Merge-Filter-Crop* would have increased precision and more points describing the object. To further validating the accuracy of this method, more analysis will be done in the case study.