Balancing Scales: Documenting a 17th Century Adobe Structure for its Holistic Assessment and Conservation using Multiple Scales of Level of Detail

Elyse Hamp [1], Miquel Reina Ortiz [2], Damiano Aiello [1], Luigi Barazzetti [3], Mario Santana Quintero [1], Elena Macchioni [4], Benjamin Marcus [4]

[1] Carleton Immersive Media Studio, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario, Canada, K1S 5B6 – elysehamp@cmail.carleton.ca, damianoaiello@cmail.carleton.ca, mariosantana@carleton.ca
[2] Université de Montréal, 1375 Avenue Thérèse-Lavoie-Roux, Montréal, Québec, Canada, H2V 0B3 – miquel.reina.ortiz@umontreal.ca
[3] Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy – luigi.barazzetti@polimi.it
[4] Getty Conservation Institute, 1200 Getty Center Drive, #700, Los Angeles, California, United States, 90049 – emacchioni@getty.edu, blmarcus@getty.edu

Keywords: Adobe Architecture, Level of Detail, Laser Scanning, Ortho-Corrected Image, Finite Element Model, Earthen Heritage.

Abstract

Level of Detail is a critical parameter of cultural heritage documentation work, which describes the amount of information presented at a given geometrical scale of representation. Within the parameter of LOD, precision, completeness and accuracy constraints are used to control the quality of the recorded data. These parameters are therefore key constraints throughout the planning, acquisition, and processing workflow for documenting a cultural heritage site. These were the key concerns during the documentation of the Church of Santo Tomás de Aquino in Rondocan, Perú. This project was conducted through collaboration between the Carleton Immersive Media Studio, the Getty Conservation Institute, and the Dirección Desconcentrada de Cultura de Cusco, local branch of the Ministerio de Cultura de Perú in 2024, with the objective of producing a comprehensive set of digital assets for the conservation of the site. By controlling the precision, completeness and accuracy of data throughout the surveying process, involving geodetic surveying, laser scanning, and photogrammetry, a high baseline of the quality of the data was maintained throughout the project, and from there an appropriate Level of Detail was possible for each digital asset, including a solid model for structural analysis, ortho-corrected images, and architectural drawings.

1. Introduction

Level of detail (LOD) is a critical technical parameter in the documentation of cultural heritage. It describes the density of information presented at a given geometrical scale and can be categorically defined according to specific amounts of graphical information (Historic England, 2024). Across the field of architecture, engineering, and construction (AEC), distinct levels of detail have been standardized specifically for application to building information modelling (BIM) (Banfi et al., 2018). This standardization is successfully applied to new and common modern construction typologies for BIM. However, standardized LOD is challenging for application to historic structures due to the geometric anomalies that typically characterize these structures (Fai & Rafeiro, 2014). These anomalies stem from non-standardized scales of architectural and structural elements, geometric irregularities due to damage or deterioration, and irregularities introduced at the time of construction.

In the documentation of cultural heritage, LOD must be determined based on the purpose of the documentation work and the intended function of the data (Fai & Rafeiro, 2014). Many different processes of management, planning, assessment, or analysis may stem from the initial data gathered and processed through documentation work, for example long-term site conservation planning, adaptive reuse or building retrofit designs, development of heritage asset inventories, condition assessment of material surfaces, or others. Each of these processes rely on a distinct LOD of the processed data to complete their objectives, ranging from the site-scale down to the sub-millimetre scale. Certain processes may rely on access to a range of LOD accessible within one project. For example, in a VR application, a very high LOD may be required for components or objects that the user will interact with, while other components in the background of the virtual environment may require only a low LOD. In one example of a HBIM (a BIM for a historic structure), the LOD was correlated to the significance of the cultural heritage of a component (Graham et al., 2019).

In the documentation of the Church of Santo Tomás de Aquino in Rondocan, Perú, LOD was a key constraint throughout the planning, acquisition, and processing phases. The documentation work was carried out by the Carleton Immersive Media Studio (CIMS), a research lab at Carleton University in Ottawa, Canada, which investigates the integration of new and emerging digital technologies into workflow for the documentation of existing architecture and cultural heritage. The work was conducted in collaboration with the Getty Conservation Institute (GCI) and the Dirección Desconcentrada de Cultura de Cusco, Ministerio de Cultura de Perú. As part of the GCI Seismic Retrofitting Project (SRP) focusing on the research and conservation of sites of earthen architecture, the objective of the Rondocan documentation project was to produce a set of digital assets to support the holistic assessment of the state of conservation of the site. The digital assets would serve as a record of posterity and be used as tools to prepare for the restoration of the site, including conservation of the interior decorated elements of the church. The digital assets included solid models of the church and the bell tower, ortho-corrected images of the decorated surfaces, and architectural plans, elevations, and section drawings of the site. The ortho-corrected images and architectural drawings provided a record of the state of conservation and were used for condition assessments of the interior of the church, and the solid models were prepared for structural analyses of the church and bell tower. Structural analyses were planned for the conservation project to simulate structural loading patterns and seismic loading, from which structural damage mechanisms and vulnerabilities could be identified. This addressed a key focus of the GCI SRP, to investigate the seismic performance of various typologies of earthen construction in Peru, with the Church of Rondocan exemplifying one of four identified typologies (Cancino et al., 2012b).

The Church of Rondocan includes a main church structure and a bell tower of adobe construction with a wood truss roof. The adobe structures are a common structural typology for Catholic churches dating to the 17th century in the province of Acomayo, Perú (Cancino et al., 2012a). Around this time, many such churches were constructed as some of the first buildings in the formation of new municipalities called *reducciones*. The *reducciones* were consolidations by the Spanish of smaller indigenous settlements. Construction of many buildings in the *reducciones*, including the churches, followed governing laws and texts which prescribed the architectural design of the buildings and the urban layout. The Church of Rondocan features decorated surfaces with geometric and figurative motifs, and houses the artwork of the Jesuit painter Bernardo Bitti, whose work dates to the 16th century (Farfán, 2023). Bitti's artwork is of significant cultural importance to the village of Rondocan and serves as a primary motivation for the documentation and conservation of the Church of Rondocan. The presence of the ornately decorated surfaces, and Bitti's religious paintings, imbues the site with the dignity befitting a place of worship in the Roman Catholic faith (Cancino et al., 2012a).

In order to achieve the required LOD for the digital assets produced from the documentation of the Church of Rondocan, the quality of the data was controlled based on parameters of precision, completeness and accuracy throughout the planning, acquisition, processing, and dissemination phases of the project. This paper discusses the methodologies and results of each of these phases of the project, with a key focus of ensuring a high quality of data, repeatability of the processing, and interoperability of the disseminated assets. Section 2 discusses the methodologies used throughout the planning, acquisition, and processing phases using geodetic surveying techniques, laser scanning, digital photogrammetry, 2D architectural drafting, and 3D solid modelling. Section 3 presents the results of the project and discusses the impact of controlled data quality on the end-use of the digital assets, and their role in supporting the holistic conservation of the site.

2. Methodology

The documentation of the Church of Rondocan was designed based on principles of data quality, reliability, and repeatability, in line with best practices for the documentation of cultural heritage sites, and followed a workflow of planning, data acquisition, processing, and dissemination (Historic England, 2024). The documentation work was conducted during a 2-week field campaign in April 2024, with processing and dissemination carried out from April to August 2024. Planning was conducted ahead of the field campaign to prepare the on-site schedule of data acquisition, determine the required documentation equipment, and test photogrammetric data acquisition setups to mitigate issues from previously identified challenging on-site conditions. Details of the planning are discussed further in the following sections.

2.1. Acquisition

On-site documentation was captured through a variety of methods to complete the scope of the project. The primary methods used were Global Navigation Satellite System (GNSS) and total station surveying, drone and terrestrial photogrammetry, and 3D scanning. The work included the use of the following digital recording equipment:

- GNSS with a geodetic receiver
- Reflectorless Electronic Distance Measurement (REDM) total station
- An Unmanned Aerial System (UAS) or drone
- 3D terrestrial laser scanner
- Mirrorless digital single lens reflex (DSLR) cameras with lighting control systems

2.1.1. Geo-spatial Positioning

To geographically orient the recorded data of the project site, surveying was employed to establish a control network based on GNSS coordinates across the site of the Church of Rondocan. An Emlid REACH RS2 GNSS receiver was used to record geo-spatial positioning data from satellites at three established positions on the site.

The acquisition was executed in static mode, recording raw data for each location. Each measurement session lasted over 3 hours to obtain redundant information with variable satellite geometry around the GNSS antenna. Raw data were saved using the Rinex format and post-processed using Precise Point Positioning (PPP). Geographic coordinates (latitude, longitude, ellipsoid elevation) were estimated in the ITRF2020/IGS20 Reference Frame. Cartographic coordinates (East, North, Orthometric elevation) were calculated using the UTM projection, Zone 19 South. The geoid model used was EGM2008.

The three GNSS points were connected to a larger network of points that were recorded across the site, surveyed with a Leica Geosystems TS11 R500 Total Station. The GNSS points allowed the transformation of the local network into the UTM coordinate system for Zone 19 (South).

Three types of points were measured across the site: mini-prism reflector, reflective tape, and reflectorless targets (checkerboard targets and natural points). The mini-prism was used to measure points that were acquired with the GNSS, and some existing stable points (nails) found on-site, which were likely positioned during previous surveying activities. Points were captured around the site using reflective tape and in reflectorless (or laser) mode to capture points on the buildings. The reflective tape targets were placed on exterior surfaces around the site, as well as interior surfaces of the church, in locations approved by the GCI team. They were placed in specific locations to remain in place over the medium to long term, providing repeatability of surveying and maintaining a connection to the established geodetic network, in case of future documentation activities.

The reflectorless mode was used to record the position of checkerboard (3D Scanner) targets, which were temporarily placed throughout the church, the tower, and the site during laser scanning. These targets were used to register the laser scans geo-spatially and were removed at the end of recording activities. First, a network was established across the site, including some laser scanning targets (already placed) and additional reflectorless tapes. Additional station points were then established across the site to add more laser scanning targets, using back-resection on the previously adjusted targets, often achieving precision better than ±1mm. All the points recorded across the site with the total station formed a set of control points, enabling the geographic referencing of the data recorded on the site and linking all the recorded areas: the interior of the church, the bell tower, and the site exterior. This network was transformed into the cartographic system using a rigid transformation based on a roto-translation without scale variation. The choice of a cartographic reference system leads to a scale factor for distances. However, as the aim was to produce a model without a modification of the effective distances due the adoption of the Universal Transversal Mercator (UTM) projection, the transformation of the local network into the cartographic system was carried out fixing the scale factor to 1, and estimating a rotation in the horizontal plane, and a 3D translation vector. The residuals of the transformation were less than 0.015 m, confirming the quality of GNSS measurements and the consistency between total station and GNSS data. In this way (i.e., using the rigid transformation) the intrinsic precision of the total station network was preserved.

A witness report detailing the coordinates and locations of the network points across the site was prepared for posterity following the data acquisition to ensure the repeatability of the processing based on the recorded survey network of the site. By providing a clear witness report of the remaining reflective tape targets and additional recorded natural points, future georeferencing and data processing can be carried out also without a new GNSS acquisition, and subsequent documentation work can be geographically referenced to the current project data, enabling interoperability of the data.

2.1.2. Laser Scanning

In order to correctly capture the geometry, and in certain areas the colour, of the existing conditions of the documented site, a Faro Focus S70 terrestrial laser scanner was used. Terrestrial laser scanners provide a fast and accurate method to document existing structures using a highly portable instrument (Stylianidis, 2016). The laser scanner uses a laser light directed across a 360° horizontal by 300° vertical field of view, which reflects off solid opaque surfaces, returning angle and distance measurements to the instrument, resulting in a 3D dense cloud of measured points surrounding the instrument from its scan location (Measur Geomatics, 2024). Images captured by the scanner over the same field of view are applied to the point cloud providing colourization of the points. By recording a series of scans in locations with overlapping coverage through a space or around a structure, the scans can be registered together in a semi-automatic way to provide a 3D point cloud of the structure.

It is important to consider the graphical scale of the resulting digital assets when laser scanning a site, to capture geometric information at a relevant level of detail for the chosen graphical scale of the digital assets. For an overall graphical scale of 1:50, ≤5 mm is the recommended maximum point density, enabling digitization of the recorded details within a range of precision between 5 to 50 mm (Historic England, 2018, 2024). With the Faro Focus S70 scanner, scans were recorded at a resolution ranging between 28.0 to 44.0 million points, which results in a point density of 6.14 to 7.67 mm between points at 10 m distance, and with an accuracy of 2 mm at 10 m distance (Faro.com, 2023). With the registration of overlapping scans capturing surfaces generally no more than 10 m away, the resolution of the resulting point cloud was kept below 5 mm. A scan quality of 3x was used throughout the scanning, with high dynamic range disabled. The scans were recorded in colour for the entire site with one exception to a spatially constrained area. At the East end of the Presbytery of the church there is a large altarpiece – a polyptych. The area behind the polyptych was a tightly confined space reaching the full height of the church, containing structural supports connecting the polyptych to the adobe walls. This area was recorded without colour because of the low light conditions. A total of 132 scans were recorded across the site. The scans of the church interior recorded the position of Bitti's paintings. Following the interior terrestrial laser scanning, the paintings were removed from the walls and securely stored while the interior terrestrial photogrammetry was conducted.

2.1.3. Photogrammetry

Photogrammetry was employed to produce ortho-corrected images of the site and the decorated surfaces on the interior of the church. The process of photogrammetry involves the processing of multiple 2D images providing different overlapping views of a subject to produce a 3D digital reconstruction, capturing the subject's geometry and colour (Luhmann et al., 2020). The digital reconstruction can be used to generate an ortho-rectified image of the recorded feature, providing a rigorous 2D ortho-image which considers the 3D surface of the captured object. A photogrammetrically constructed ortho-rectified image, referred to here as an ortho-corrected image, can provide precise measurements for captured features and portray details at very high resolutions, which is critical for recording features such as the decorated surfaces on the interior of the Church of Rondocan.

Two methods of photogrammetry were employed on this project: terrestrial photogrammetry, and aerial photogrammetry using an unmanned aerial vehicle (UAV), or drone. Both the terrestrial and drone photogrammetry were conducted following the 3 x 3 rules for photogrammetric documentation regarding geometry, camera, and procedure in photogrammetric data acquisition (Waldhäusl & Ogleby, 1994). These rules ensure best practices for image overlap, coverage of the recorded feature, and data organization. For both terrestrial and drone photogrammetry, photographs were captured with at least 60% overlap between sequential images. The standards for ground sample distance (GSD) were agreed upon with the GCI to achieve the desired resolution of ortho-corrected images and meet graphical scale requirements.

The aerial photogrammetry data acquisition was carried out with a Mavic Air 2S UAV and a Mavic 3 Pro drones, using both manual and automatic flight. In the case of automatic flight, the mission was planned and executed using the Dronelink application. The Mavic 3 Pro was manually operated to create a detailed point cloud and high resolution ortho-corrected image of the church. The choice to utilize a manual acquisition was due to the irregular site topography, with a notable difference in elevation along the longitudinal axis of church. In addition, some elements such as the surrounding buildings, the bell tower, and the external wall did not allow a safe acquisition with an automated flight, especially for the external elevations. The flight was manually conducted by an operator who maintained contact with the drone, obtaining a rigid image network around the church. A total number of 700 images were acquired using the drones and processed with Agisoft Meteshape Pro (Figure 1). A set of control points were included in the project and provided an overall registration error better than 5 mm.

A second flight was conducted with the Mavic Air 2s, using a higher elevation to capture the site context, including the square and some surrounding buildings. The flight was automatic, using a double grid scheme, with an overlap better than 80% for both longitudinal and transversal directions. The elevation above ground level was about 35 m, which was measured considering the take-off point. From the aerial photogrammetry, two ortho-corrected images were produced in the UTM 19 South cartographic reference system. The ortho-corrected image produced from the Mavic 3 Pro images was processed to a higher level of detail with a GSD of 7 mm for the church, whereas the Mavic Air 2s ortho-corrected image covers a larger extent (including the adjacent town square) and has a GSD of 10 mm.

Figure 1. Camera positions of drone images captured with the Mavic 3 Pro.

Terrestrial photogrammetry was a critical component for recording the interior decorated surfaces at a very high resolution; 0.5 mm GSD. The purpose of achieving this resolution was to capture the current condition and the details of the geometric patterns and motifs painted onto the plaster finishing of the church walls, to be able to record conditions prior to any conservation work on the decorated surfaces. Terrestrial photogrammetry presented significant challenges due to low natural lighting, high ceilings, complex surfaces, and obstructed areas. Testing was conducted during the planning phase to determine the appropriate equipment and controlled lighting setup to capture images for terrestrial photogrammetry inside the church. The testing was conducted at the CIMS lab using the same equipment intended for the field campaign. A Sony Alpha 7 IV mirrorless full frame camera was used with two different lenses with focal lengths of 35 mm and 55 mm. To simulate similar photogrammetric conditions inside the church, the camera and lighting equipment were set up in the lab with negligible natural lighting and at the maximum achievable distance of 7 meters between the camera and the opposite wall, replicating site constraints. This distance was maximized to minimize the angle of inclination of the photos and mitigate the need for a scaffolding system to capture images at higher elevations on the walls. The camera was elevated approximately 3 metres above ground by holding the tripod in an extended overhead position to minimize the inclination angle. A lighting system of three flashes and umbrellas was set up around the camera stationed on a tripod, and different flash power outputs, focal lengths, shutter speeds, and apertures were tested by taking photos of the opposite wall up to a height of 8 metres, simulating the interior church walls. During data acquisition for the church interior, the flash power was varied from ¼ for images taken close to the ground, up to full power in certain areas close to the ceiling. Lighting conditions in each space in the church were measured with a Sekonic light meter, and the camera settings were determined accordingly. Throughout the church interior, the negligible natural lighting and controlled flash lighting system was optimized with a shutter speed of 1/125, an aperture of f5.6, and ISO 800. With a maximum distance of 7.5 m between the camera and the recorded surfaces achieved by extending the tripod overhead, the GSD of the resulting ortho-corrected images was kept below 0.5 mm. The GSD was calculated based on the following equation (Luhmann et al., 2020):

$$\frac{f}{H} = \frac{pixel\ size}{GSD} \quad (1)$$

where f = camera focal length
H = distance from subject
$pixel\ size = \frac{camera\ sensor\ width}{image\ width}$
GSD = desired ortho-corrected image resolution

In the more confined spaces of the choir loft and the vestibule (*coro alto* and *soto coro*) inside the church, a 35 mm lens was used and the maximum distance from the recorded surfaces was 4.8 m.

2.2. Processing

2.2.1. Laser Scanning

Laser scan registration was conducted using Faro Scene version 2019 based on the alignment of targets across overlapping scans. Checker-board targets were used throughout the scans of the interior and exterior of the site. The checker-board targets were captured by the laser scanner as well as measured with the Total Station in order to geographically reference the scans into the UTM coordinate system for Zone 19 (South). Laser scanning spheres with a recognized consistent diameter were also used as targets for the scan registration, since they can be recognized in a scan captured from any angle. Throughout the scanning process, the targets were spatially distributed around the site, ensuring that at least three targets were visible in each scan, and each target was visible in at least two scans.

Figure 2. Views of the registered point cloud in (a) perspective view, (b) longitudinal view, and (c) lateral view.

The scans for the entire site, including the church and bell tower interiors and the site exterior, were registered together in one project using target-based registration, with a resulting registration precision better than ±5 mm. The registered scans were exported as E57 files, which were imported into Recap for logical grouping of the spaces across the site. Recap was used to group the scans into four areas, including the church interior, the tower interior, the area behind the polyptych, and the site exterior. Some cleaning was done in Recap to remove unnecessary obstructions and reflections in the point clouds, such as people, animals, random points captured at extreme distances from the scan locations (Figure 2). The final point clouds were attached to

AutoCAD to produce measured line drawings and to Rhino to produce a solid model for Finite Element Analysis.

2.2.2. Digital Photogrammetry

Photogrammetric processing for this project was conducted using Agisoft Metashape Pro, with drone and terrestrial datasets processed separately. Drone photogrammetry was processed without any colour calibration or editing of the acquired images, as the resulting point clouds were primarily used as a geometric record of exterior spaces that were inaccessible to terrestrial laser scanning. Therefore, calibrated colour of the point clouds was not necessary.

For the terrestrial photogrammetry, RAW images were first white balanced, and colour corrected using Adobe Camera Raw by referencing the colour calibration card photographed in each area of the church (Figure 3). The white balance adjusts the colour temperature of the captured images, and the colour correction adjusts the colour profile of raw images, which is influenced by the device used to capture the image. The colour profile used in Adobe Camera Raw was generated with X-Rite ColorChecker Camera Calibration software, based on the colour calibration card image from each corresponding area of the church. The edited images were then exported in JPG file format for processing in Agisoft Metashape Pro.

Figure 3. Unedited image (left) compared with white balanced and colour calibrated image for terrestrial photogrammetry (right).

A general workflow of image orientation, meshing, texturization, and orthomosaic generation was followed to produce ortho-corrected images of the interior decorated surfaces (Figure 4). Each area of the church interior was processed separately based on the physical extents of the recorded surface. The edited images were imported into Metashape Pro, checked for quality, and aligned using the high-quality setting to produce a sparse cloud and obtain exterior orientation parameters. A mesh was then generated based on depth maps, creating a 3D polygonal surface representative of the recorded geometry. Based on the targeted GSD considered in the data acquisition, a very fine mesh can be achieved which shows small changes in the geometry of the recorded surface. These details are valuable for understanding instances of damage or deterioration on the material surfaces.

The mesh was textured by projecting high-resolution colour from the oriented images onto the mesh surface. The photogrammetric model was geo-referenced using the coordinates of natural points visible both in the images used for the photogrammetric model and in the geo-referenced point cloud generated from laser scanning. The coordinates of the natural points were measured from the RealView in Autodesk Recap. Markers were created in Metashape, defined with the measured coordinates, and placed in the precisely measured position visible from at least three images. Each marker was typically placed in more than six images to achieve good precision in the geo-referencing. This process allows for flexibility in the choice of natural points used to geo-reference the photogrammetric model; rather than relying on a limited number of pre-determined natural points measured with a Total Station during the field campaign, natural points can be identified and measured during the processing phase.

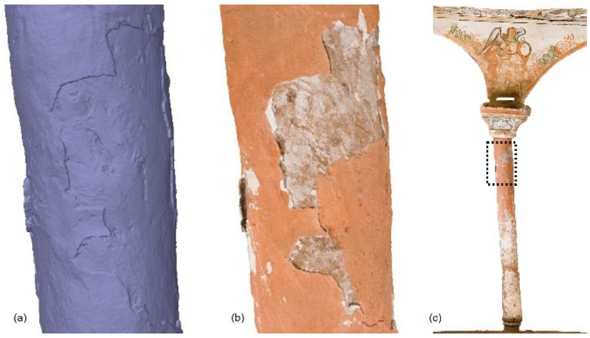

Figure 4. Photogrammetric results of an interior column showing (a) the mesh, (b), the textured mesh, and (c) the complete ortho-corrected image.

Ortho-corrected images were generated for each orientation of the photogrammetric models to align with the orientations of the measured line drawings. To ensure the resulting ortho-corrected images aligned with the associated drawing, the coordinates of the origin of the user coordinate system (UCS), a point along the x-axis of the UCS, and a point along the y-axis of the UCS of the measured line drawing were measured and input as markers in the geo-referenced photogrammetric project. The ortho-corrected images were generated using the UCS coordinate markers to establish the x and y-axes for the projection, and the resolution was rounded up to the target GSD of 0.5mm for each interior decorated surface. The resulting ortho-corrected images were exported as geographically referenced TIFF files with world files (TFW file format) to define their geographic coordinates according to the associated drawing UCS.

Terrestrial photogrammetry of the church interior was also used as a reference to trace the geometry of the interior architecture in areas that were covered by Bitti's paintings during the laser scanning. In this case, a dense cloud was generated for the geo-referenced photogrammetric project and exported in E57 format. The E57 file was imported into AutoDesk Recap and converted into RCP file format, which was then attached to the measured line drawing in AutoCAD. This process was used specifically to capture the geometry of an interior window opening on the south wall of the Nave (*muro de la Epistola*). A window opening was identified from the exterior point clouds and photographs but was not visible in the interior laser scan point cloud behind Bitti's painting.

3. Results

Two sets of digital assets were generated from the processed data discussed in the previous section. First, a set of measured line drawings illustrating the architecture and details of the site in plan, elevation, and section were created and overlaid with the ortho-corrected images. Second, a solid geometric model was developed to be interoperable for structural analysis using Finite Element Method-based software.

3.1. Measured Line Drawings

A set of plan, elevation, and section drawings at different scales were determined in collaboration with the GCI and prepared using AutoCAD 2024 drafting software in DWG file format, provided as AutoCAD 2018 DWG files for compatibility with older versions of the program. From these drawings, the site layout, the architecture of the church and the tower, and details of the interior decorated surfaces could be understood. A set of consistent drawing scales were determined for the site including 1:300 for the site plan, and a combination of 1:150 and 1:50 for the elevations and section drawings. Section drawings were prepared through relevant longitudinal and lateral sections of the church and the tower. The sections were oriented to the closest door and window openings to provide clear representations of the relevant architecture.

To facilitate repeatability of the processing, drafting conventions were followed to create the measured line drawings. In each DWG file, the point clouds were attached and oriented according to the referenced UTM coordinate system, and a UCS was established for each relevant plan, elevation, and section. The UCS were defined by tracing reference lines around and through the structures, orthogonal to each elevation.

In the section drawings, section planes were created and positioned according to the orientation of the UCS to section through the point cloud at the corresponding locations. The sections were traced starting from a slice thickness of 5 mm to capture the section cut through the building. The slice thickness was increased in small increments to visualize additional details in the point cloud, until the complete plane of the building was visible.

The measured line drawings were created by tracing the details visible from the point clouds recorded by laser scanning. The point clouds were visualized in two modes to optimize the representation of different details: normal and scan colour, which show the points in a colour way indicative of the normal direction of the recorded surface, and the original colours of the point cloud captured during the scanning process, respectively. In areas with negligible lighting where the scans were recorded without colour, the original scan colour appears grayscale. Based on the largest scale used for the elevations, sections, and plans, these drawings were traced at a LOD such that the smallest captured detail was 10 mm. For the site plan, drawn at a scale of 1:300, the LOD was adjusted so that the smallest represented detail was 60 mm.

The drawings were traced with a pre-defined system of layers, established based on architectural conventions for conveying scale, depth, level of detail, and annotations (Historic England, 2024). The final drawings were plotted according to the plot styles specified for each layer, which were defined in separate CTB files: one for the 1:50 scale drawings, and another shared by the 1:150 and 1:300 scale drawings.

3.2. 3D Solid Model

The second objective of the documentation work for the Church of Rondocan was the production of a simplified 3D solid model of the church and tower geometry for structural analysis. The structural analysis was planned to be completed based on the Finite Element Method, requiring 3D tetrahedral meshes of the structures.

The end-use of the solid model would be FEM-based seismic analyses of the church and the tower, which would include simulations of structural loading and seismic ground motions on the structures. These analyses were to be led by GCI consultants and specialists in the analysis of unreinforced masonry structures, with the objective of understanding the potential failure mechanisms of the adobe structures based on the seismic zone in which the Church of Rondocan is situated.

Prior to developing the solid models, the structural morphology of the church and tower was assessed to identify distinct components of the structure, determine the type of geometry to use to represent each component, and define the modelling precision. Three distinct structural components were identified based on on-site investigation and reference to reports on similar structural typologies (Cancino et al., 2012a). This included the adobe walls, the stone foundations, and the timber roof truss and crossbeams. The adobe walls and stone foundations were decided to be modelled as 3D solid geometry, which could be meshed as 3D tetrahedral continuums, to simplify the behaviour of the masonry into a homogenized continuum. This simplification is the basis for Finite Element-based analysis of unreinforced masonry (D'Altri et al., 2020; Lourenço, 2009). In consultation with the GCI project collaborators, the timber truss members and crossbeams were modelled using simple line segments. With these modelling decisions, a level of precision was determined for the modelling process of each component.

Adobe masonry inherently represents a high level of geometric irregularity due to the irregular shapes and surfaces of adobe blocks, the mud and plaster surface finishing, and in the case of this site, the deterioration of the adobe and plaster caused by water infiltration and lack of maintenance. Following a very high LOD in the solid model, as has been done on other solid modelling projects for stone-based masonry structures, such as in Banfi et al. (2018), was not feasible for this project because of the inherently high irregularity and the required interoperability of the models with FEM-based programs. So, to ensure the operability of the final 3D tetrahedral mesh in the FEM-based program, the solid model was developed at a low LOD based on the point clouds of the structure, and secondary meshing programs were employed to test the meshing process and identify geometric errors. A precision tolerance of $\pm$ 20 cm from the point clouds was employed throughout the modelling process of the adobe and the stone foundations. For the timber components, the nodes of the endpoints of the line segments were modelled at the centre of the connections with the adobe, using a simplified straight-line segment connecting each end rather than following any warping in the timber visible in the point clouds.

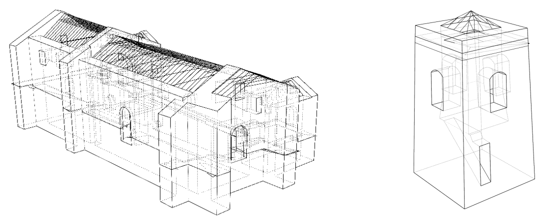

Figure 5. Solid models of the church and tower of the Church of Rondocan.

Following these modelling decisions, the solid model was developed in Rhino 8.0, using non-uniform rational B-splines (NURBS) to model the 3D geometry of the structures (Figure 5). NURBS are mathematical representations of 3D geometry which can be converted into a 3D mesh formed of tetrahedrons for Finite Element Analysis (Chellini et al., 2014). NURBS geometry is described by degree, control points, knots and an evaluation rule; these parameters together result in the mathematical description of various geometry,—form a 2D line, to a circle, arc, or curve which can form complex 3D surfaces or solids (Robert McNeel & Associates (TLM, Inc.), 2024). The solid models were created with reference to the church and tower point clouds captured from laser scanning, using Veesus Arena4D in Rhino to attach and manipulate the point clouds. The point clouds were interpreted using section cuts to understand wall thickness and

https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-557-2025 | © Author(s) 2025. CC BY 4.0 License.

the geometry of openings, niches, and timber components throughout the structures. The geometry was created by extruding closed planar curves into 3D solids, and then manipulating the geometry using the control nodes and edges as required. Boolean operations were used to unionize and split 3D solids such that each structure is defined by mostly one continuous solid. Discrete solids were defined for the adobe walls and the stone foundations of the church. Polyline tools were used to model the timber components of the roof as straight-line segments, including the rafters and crossbeams that run laterally through the church, and which meet at the central peak of the tower.

In preparation for final meshing for structural analysis, the model geometry was validated through two open-source programs: Analysis Situs and GMSH. Analysis Situs was used to validate the mathematical logic of the 3D geometry, to check for open edges and non-manifold edges. GMSH was used to process a basic mesh from the 3D geometry, which was used to detect any small edges or illogical geometry that would prevent proper meshing in the FEM software used for the final structural analysis. Variations in tetrahedral mesh size were tested using GMSH, employing mesh sizes in the sub-metre range following best practices for Finite Element meshing of unreinforced masonry (Lourenço & Gaetani, 2022). These two validation methods facilitated the interoperability of the solid model with the software use for FEM-based analysis. For the analysis, the final solid model was provided in 3DM and STP file formats.

4. Conclusion

Throughout the documentation process for the Church of Rondocan, LOD was a key consideration. The final required LOD was determined for each digital asset on the project, including measured line drawings, ortho-corrected images, and solid models for structural analysis. Based on these determined specifications, corresponding levels of precision and accuracy were determined for the recorded data to meet the final LOD objectives (Table 1). This process of ensuring a final LOD in each digital asset began with the initial geodetic survey of the site, which served as the reference system for all subsequent georeferenced data. Therefore, the precision and accuracy of the geodetic system set the baseline for the precision, accuracy, and final LOD of all subsequent processing and digital assets.

By using a system of controlled precision and accuracy for the initial recorded data, the quality of subsequent geo-referenced and processed outputs (such as point clouds and ortho-corrected images) was effectively maintained, including parameters such as completeness, point density, and site coverage (among others). As a result, the measured line drawings have captured details as small as 10 mm, the ortho-corrected images have achieved a resolution of 0.5 mm per pixel for the interior decorated surfaces, and the solid models have been generated at a simplified LOD of $\pm$ 20 cm from the point clouds. The measured line drawings and ortho-corrected images were geo-referenced to the cartographic network with transformation residuals of less than 0.015 m. This means that the metadata of those digital assets situates them accurately in the cartographic location of Rondocan, Perú. This accurate geo-referencing opens the possibility of integrating the digital assets with data produced from other projects within the same cartographic region, or geo-referencing data recorded in future campaigns to the same system. This has implications for long-term monitoring campaigns, GIS projects, or interoperability with data acquired by other practitioners.

Documentation Step	Metric of Precision, Accuracy, or LOD
Geodetic survey – resections	Precision < 1 mm
Geodetic survey – rigid transformation of local network to cartographic system	Transformation residuals < 0.015 m
Laser scanning point density	6.14 – 7.67 mm at 10 m from scanner
Laser scanning point accuracy	2 mm at 10 m from scanner
Laser scan registration incorporating TS targets	Precision < 5 mm
Photogrammetry geo-referencing	Marker (control point) error RMSE < 5 mm
Terrestrial photogrammetry resolution	GSD 0.5 mm/pixel
Aerial photogrammetry resolution	GSD ≤ 10 mm/pixel
Measured line drawings LOD, 1:50 scale	LOD ≥ 10 mm
Measured line drawings LOD, 1:300 scale	LOD ≥ 60 mm

Table 1. Metrics of precision, accuracy, and LOD for digital asset data acquisition and processing.

Aside from other potential applications of the data, the control of data quality on this project resulted in high LOD measured line drawings and ortho-corrected images that serve the initial objectives of the GCI Seismic Retrofitting Project: to record the current state of conservation of the site's architecture and decorated surfaces. The simplified LOD solid models enable seismic analysis of the structures by specialists, allowing for the simulation and identification of potential failure mechanisms in the historic structures, and contributing to the overall investigation and conservation of the Church of Rondocan. During the initial planning phase as site reconnaissance was conducted using previous reports and archival information, several challenges to the documentation work were identified. This included constraining and obstructed spaces inside the church and poor lighting conditions affecting the data acquisition. These challenges were addressed through careful planning, simulation and testing of constraining spaces prior to the field campaign, and preparation of the appropriate equipment. The primary challenge affecting the processing phase was the validation of the 3D mesh of the church and tower models, to ensure interoperability with FEM-based software. This challenge was mitigated by employing a simplified LOD agreed upon with the GCI, and validation using two programs to assess the correctness of the solid geometry and check for inconsistencies in the generated 3D meshes.

The comprehensive documentation of the Church of Rondocan has been completed to support the ongoing conservation of the site by the Dirección Desconcentrada de Cultura de Cusco, local branch of the Ministerio de Cultura de Perú, the GCI, and their collaborators. The data acquisition, processing, and dissemination of the digital assets has been conducted in such a way to ensure interoperability of the data as well as repeatability of processing with the data. These best practices in cultural heritage documentation facilitate opportunity for future work on the project. Since the Church of Rondocan houses Bitti's artwork which is of great cultural significance, future work may include comprehensive documentation of the artwork, or further documentation of the site at different stages of its life cycle, including before and after conservation activities, or following a natural event such as damaging storms or seismic events.

References

Banfi, F., Chow, L., Reina Ortiz, M., Ouimet, C., Fai, S., & Ioannides, M. (2018). *Building Information Modeling for Cultural Heritage: The Management of Generative Process for Complex Historical Buildings* (pp. 119–130). Springer International Publishing. https://doi.org/10.1007/978-3-319-75826-8_10

Cancino, C., Lardinois, S., D'Ayala, D., Fonseca Ferreira, C., Torrealva Dávila, D., Vicente Meléndez, E., & Villacorta Santamato, L. (2012a). *Church of Kuño Tambo* (Research Report Volume 2, Chapter 5; Seismic Retrofitting Project: Assessment of Prototype Buildings). Getty Conservation Institute.

Cancino, C., Lardinois, S., D'Ayala, D., Fonseca Ferreira, C., Torrealva Dávila, D., Vicente Meléndez, E., & Villacorta Santamato, L. (2012b). *Methodology* (Research Report Volum 1, Chapter 2; Seismic Retrofitting Project: Assessment of Prototype Buildings). Getty Conservation Institute.

Chellini, G., Nardini, L., Pucci, B., Salvatore, W., & Tognaccini, R. (2014). Evaluation of Seismic Vulnerability of Santa Maria del Mar in Barcelona by an Integrated Approach Based on Terrestrial Laser Scanner and Finite Element Modeling. *International Journal of Architectural Heritage*, *8*(6), 795–819. https://doi.org/10.1080/15583058.2012.747115

D'Altri, A. M., Sarhosis, V., Milani, G., Rots, J., Cattari, S., Lagomarsino, S., Sacco, E., Tralli, A., Castellazzi, G., & de Miranda, S. (2020). Modeling Strategies for the Computational Analysis of Unreinforced Masonry Structures: Review and Classification. *Archives of Computational Methods in Engineering*, *27*(4), 1153–1185. https://doi.org/10.1007/s11831-019-09351-x

Fai, S., & Rafeiro, J. (2014). Establishing an Appropriate Level of Detail (LoD) for a Building Information Model (BIM)—West Block, Parliament Hill, Ottawa, Canada. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *II*(5), 123–130. https://doi.org/10.5194/isprsannals-II-5-123-2014

Farfán, A. (2023). La Oración en el huerto de Bernardo Bitti S. J. en Rondocan. *Letras (Lima)*, *94*.

Faro.com. (2023, June 30). *Interface Guide for Laser Scanner Focus 3D*. https://knowledge.faro.com/Hardware/Focus/Focus/Interface_Guide_for_Laser_Scanner_Focus_3D

Graham, K., Chow, L., & Fai, S. (2019). From BIM to VR: defining a level of detail to guide virtual reality narratives. *Journal of Information Technology in Construction*, *24*, 553–568. https://doi.org/10.36680/j.itcon.2019.031

Historic England. (2018). *3D Laser Scanning for Heritage: Advice and Guidance on the Use of Laser Scanning in Archaeology and Architecture*. Historic England.

Historic England. (2024). *Geospatial Survey Specifications for Cultural Heritage*. Historic England.

Lourenço, P. B. (2009). *Recent advances in masonry modelling: Micromodelling and homogenisation* (pp. 251–294). Imperial College Press. https://doi.org/10.1142/9781848163089_0006

Lourenço, P. B., & Gaetani, A. (2022). *Finite Element Analysis for Building Assessment: Advanced Use and Practical Recommendations* (1st ed.). Routledge. https://doi.org/10.1201/9780429341564

Luhmann, T., Robson, S., Kyle, S., & Boehm, J. (2020). *Close-range photogrammetry and 3d imaging* (3rd edition). Walter de Gruyter GmbH.

Measur Geomatics. (2024). *Faro Focus Laser Scanner*. https://geomatics.measur.ca/products/faro-focus-laser-scanner

Robert McNeel & Associates (TLM, Inc.). (2024). *What are NURBS?* Www.Rhino3d.Com. https://www.rhino3d.com/features/nurbs/

Stylianidis, E. (2016). *Basics of Range-Based Modelling Techniques in Cultural Heritage 3D Recording*. Whittles Publishing Ltd.

Waldhäusl, P., & Ogleby, C. (1994). 3-Rules for simple photogrammetric documentation of architecture. *International Archives of Photogrammetry and Remote Sensing*, *30*, 426–429.