Integrated Workflow for 3D modelling of Historic Architecture: A Multi-Sensor Approach

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***Abstract* – The proposed work presents an integrated approach for the three-dimensional digitisation and parametric modelling of a historic building, specifically the Church of "Sant'Antonio dei Cappuccini". The survey involved the combined use of photogrammetric surveys from Unmanned Aerial Vehicle (UAV) and scanning using a handheld Laser Scanner. This multi sensors approach allowed to obtain a detailed point cloud of the structure in rapid and accurate way; in addition, an advanced workflow was implemented to transform the point cloud into a Non-Uniform Rational B-Splines (NURBS) model capable of faithfully representing the complex architectural geometries. Unlike mesh models, which are based on a polygonal approximation of geometry, NURBS are based on mathematical formulas capable of producing continuous and editable surfaces with a high degree of control, maintaining a high level of accuracy compared to the original model. Therefore, this methodological approach can be replicated in different contexts, particularly for historical and architectural structures, as well as being interoperable within other workflows such as HBIM (Heritage Building Information Modelling).**

I. INTRODUCTION

The possibility of generating 3D models of structures belonging to the architectural and cultural heritage has become an indispensable basis for implementing policies for the conservation, preservation, restoration, and enhancement of cultural heritage. Thanks to integrated surveying technologies, such as UAV photogrammetry, Terrestrial Laser Scanner (TLS) and handheld laser scanners, it is possible to acquire detailed geometric information, even in complex and difficult-to-access contexts [1,2]. The methodology of merging aerial and terrestrial data for 3D modelling of historical architecture is of fundamental importance to obtain a continuous and complete model of the investigated structure [3,4].

Numerous studies have highlighted the effectiveness of the multi-sensor approach for the documentation and modelling of historic buildings. In this context, for example Mozas-Calvache et al., 2024 [5] applied multi-sensor geomatics techniques to the Church of San Miguel in Jaén, Spain, obtaining a high-resolution integrated model. Palomba et al., 2021 [6] documented the Church of Sant'Agnello Abate in Maddaloni using multi-sensor techniques, demonstrating how the use of portable laser scanners allows for considerable operational flexibility. However, the complexity of the raw data acquired requires the adoption of structured methods for its processing and transformation into interoperable and parametric digital models that can be used in multidisciplinary contexts. NURBS (Non-Uniform Rational B-Splines) modelling is one of the most advanced and versatile techniques for representing complex three-dimensional geometries, establishing itself as an indispensable tool for the precise mathematical representation of surfaces and curves [7]. This technique makes it possible to model surfaces of arbitrary degree with good accuracy, including arches, organic geometries, etc., overcoming the limitations of traditional polygonal representations [8]. Therefore, in the context of the digitisation of cultural and architectural heritage, NURBS surfaces offer the advantage of faithfully reproducing complex and continuous geometric details, facilitating the creation of high-precision digital models [9]. Furthermore, their parametric nature ensures interoperability and modifiability, which are fundamental aspects in workflows for the restoration, conservation, and digital enhancement of cultural heritage. In particular, Barazzetti et al., 2016 [10] adopted NURBS modelling to obtain BIM models of the Azzone Visconte bridge in Lecco, while Banfi et al., 2018 integrated free modelling and NURBS algorithms with BIM to accurately represent the complex geometries of historic buildings [11]. In the latter manuscript, the authors have demonstrated how the use of NURBS surfaces not only allows for faithful reconstruction of geometries, but also constitutes a crucial step towards the creation of interoperable digital models that interact with modern information environments (BIM/HBIM) and simulation software, thus ensuring greater longevity and adaptability of the acquired data.

The proposed work is part of a research and experimentation programme that aims to consolidate the adoption of NURBS techniques [12, 13] as the context of 3D modelling in cultural heritage. In particular, the paper proposes an integrated operational methodology applied to the Church of Sant'Antonio dei Cappuccini, a building of historical and artistic importance located in Martina Franca (TA), Italy. The choice of this building stems from the decision to tackle an architectural style characterised by highly complex geometry and significant historical stratification, elements that make it essential to adopt advanced surveying and modelling techniques.

II. METHOD

For the case study analysed in this paper, an integrated methodology based on the combined use of data acquisition technologies was adopted. In particular, the architectural elements inside the structure were scanned with a handheld laser scanner in order to obtain high-density, high-quality data. For the exterior, a UAV equipped with a high-resolution camera was used to perform a photogrammetric survey, allowing the generation of a point cloud (PC) obtained using Structure from Motion (SfM) and Multi View Stereo (MVS) algorithms. The processing was carried out by first registering the two PCs and then georeferencing the model using coordinates obtained with Global Navigation Satellite System (GNSS) technology. The overall point cloud was then imported into Cloud Compare software, where it underwent a careful cleaning, noise removal and optimisation phase, through decimation and filtering operations and subsequent subsampling. In general, subsampling can be classified as:

- Voxel Grid Downsampling: divides the space into cubic cells of side III (voxels) and replaces all points within each voxel with a representative point (e.g. the barycentre or the midpoint). In fact, Equation (1) is used to determine the barycentre of a total set of points in the point cloud:

$$\overline{p_v} = \frac{1}{N_v}\sum_{j=1}^{N_v} p_J \qquad (1)$$

where:

p_v represent the points contained in the voxel;
N_v total set of point in the point cloud;
p_J represents a single point in the point cloud.

- Uniform Sampling: selection of points at regular spatial intervals, often on the surface.
- Poisson Disk Sampling: generates a sample in which points are distributed uniformly but with a defined minimum distance, ensuring local homogeneity as shown in the following Equation (2):

$$\|p_i - p_j\| \geq r_{\min} \quad \forall i \neq j \qquad (2)$$

which represents a minimum distance constraint between points where:

p_i, p_j represent two distinct points in the point cloud;
$\|p_i - p_j\|$ Euclidean distance between points;
$r_{\min}$ predefined minimum radius value

In addition, useful sections were extracted in Cloud Compare Software for the analysis of the main geometries chosen according to the complexity of the elements constituting the structure and necessary to better represent the main architectural features. Finally, the optimised cloud and sections were imported into Rhinoceros 3D, where the three-dimensional modelling of the building was carried out using NURBS surfaces, which express the mathematical representation of 3D geometries, capable of precisely defining any shape. following the theory of Bezier curve models [14] and expressed by the following Equation (3).

$$\sum_{i=1}^{n} \frac{N_{i,n}(u)\cdot w_i}{\sum_{j=1}^{n} N_{j,n}\cdot w_j} P_i \qquad (3)$$

where:

w_i weights;
P_i control points;
$N_{i,n}$ are the normalised B-Spline basis function of n degree.

In particular, NURBS can be created using a series of parameterised commands that regulate their complexity:

- Sweep 1 Rail: extrusion along a single guide curve.
- Sweep 2 Rails: extrusion along two guide curves.
- Loft: interpolation between sequential curves with smooth surfaces.
- Revolve: generation of surfaces by rotation around a real or apparent axis of symmetry.
- Surface from Network of Curves: construction from a grid of intersecting curves.
- Patch: complex interpolation on multiple curves, useful for filling irregular or complex areas.

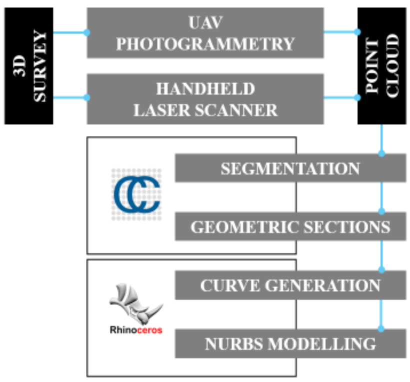


Fig. 1. Methodological approach pipeline

Using this methodological approach, it was possible to produce an accurate and detailed three-dimensional model of the internal and external architecture of the structure. The pipeline shown in Figure 1 summarises the methodological approach used.

III. CASE STUDY

A. Brief historical notes

The current Church of "Sant'Antonio dei Cappuccini" with its adjoining convent was built in the 16th century on the site of a previous settlement of Basilian monks. It houses a painting of the Madonna dell'Odegitria, which is believed to be the reason why the surrounding area was named "Valle d'Itria" in the Modern Age (Figure 2).

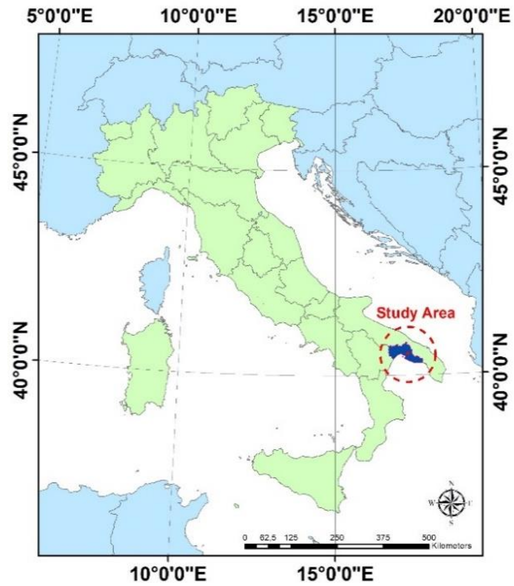


Fig. 2. Keymap of the study area. The church is located in the Apulia region, in the municipality of Martina Franca, a town located near the city of Taranto, Italy.

The current church was built in 1590, as indicated by the date engraved on the portal's entablature. On the façade, just above the niche with the Immaculate Conception, another date is engraved: 1698. This indicates the renovation of the façade based on a design by a friar who was an architect and master stonemason. The façade has no particular decorations, except for the bell gable with Baroque features on the left side, which was built in 1757, as clearly indicated by the inscription on the arch. Next to the church is the Capuchin monastery. The church has a longitudinal plan with three very deep chapels on the left side, while on the other side there is only one chapel, which is equally deep. The interior of the church is notable for the refined woodwork decorating each altar with two-tone inlay. In addition to the chapel housing the painting of the "Odegitria", the high altar, built in 1773, and the wooden choir dating back to 1750 are also of particular importance.

B. UAV photogrammetric survey

In order to develop an accurate three-dimensional representation of the external architecture of the area under study, a photogrammetric survey was carried out using a UAV. Specifically, a DJI Mavic 2 PRO drone was used, which allowed a dataset of 519 images with a resolution of 20 MP to be acquired. In order to georeference the model in the RDN2008-UTM33N reference system (EPSG:6708), a GNSS survey was performed; 11 Ground Control Points (GCPs) were acquired in Post-Processing Kinematic mode using a Leica GNSS 12 receiver. The data was post-processed with Leica Infinity proprietary software using the raw data in Rinex format recorded by the nearest permanent station. Once the baselines between the base station and the rover had been processed, it was possible to determine the position solutions for each point surveyed. The images were processed using Agisoft Metashape photogrammetry software, which allowed the processing of a dense point cloud consisting of over 40 million points (Figure 3), with a process accuracy in terms of Root Mean Square Error (RMSE) of 0.03 m. In addition, in order to improve the quality of the point cloud and reduce noise and objects outside the scene that were not included in the subsequent modelling phase, the PC was cleaned up manually. As a result, it was possible to generate a point cloud of approximately 47 million points.

Fig. 3. Point cloud of the external structure generated by photogrammetric survey from UAV.

C. 3D surveying with handheld TLS

A handheld laser scanner, model XGRIDS LIXEL L2, was used to survey the interior of the Church. This device uses Time of Flight (TOF) technology with multi-echo acquisition and mobile scanning capability (Mobile Mapping mode). The device stands out for its high portability and ability to perform surveys in complex and articulated environments without the use of fixed tripods, significantly reducing acquisition times compared to traditional static TLS. Furthermore, this equipment has enabled continuous data collection with an acquisition frequency of over 640,000 points/second, a range of between 0.50 m and 120 m and a sensor field of view of 360°×270°, ensuring adequate density and accuracy even in poorly lit indoor environments or those with complex geometries, such as altars, side chapels and vaults. (Figure 4). The integrated inertial localisation and Simultaneous Localisation and Mapping (SLAM) technology also made it possible to maintain alignment between scans even in the absence of a GNSS signal, a key feature in indoor environments. Furthermore, unlike photogrammetry, which requires longer processing times for three-dimensional reconstruction using SfM/MVS algorithms, this equipment provided a georeferenced point cloud almost immediately, reducing the overall working time. This approach enabled complete, rapid and accurate three-dimensional documentation of the church's interior, facilitating subsequent processing and 3D modelling and producing a PC of over 50 million points.

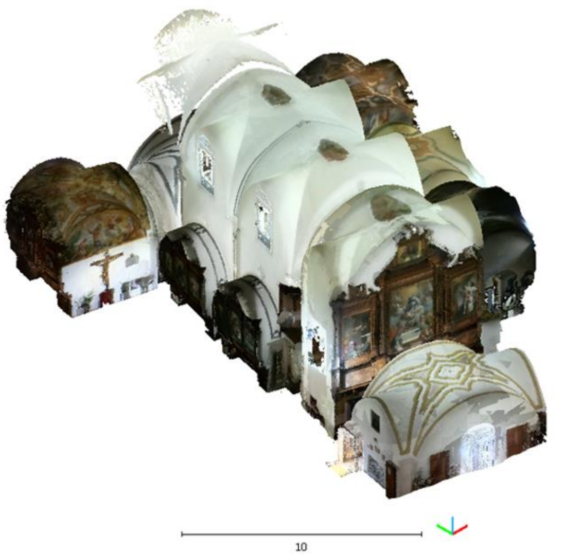


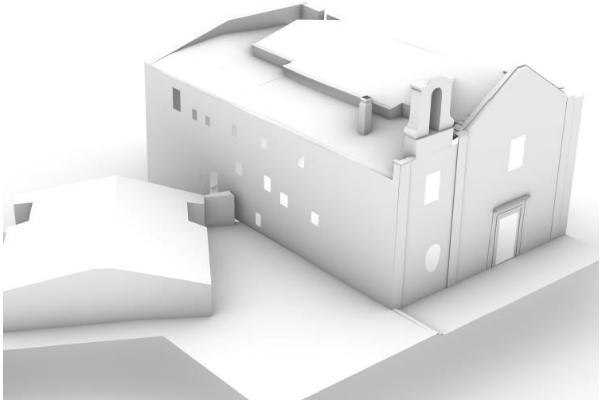
Fig. 4. Point cloud obtained by XGRIDS LIXEL L2 *handheld laser scanner.*

D. 3D modelling of historical architecture

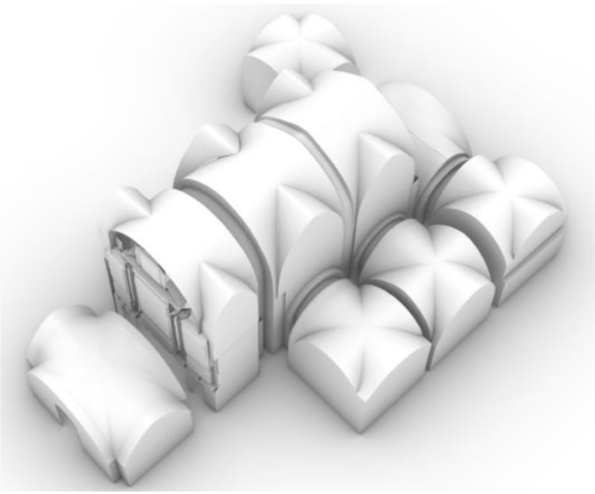
For the 3D modelling of the case study analysed, the first phase consisted of cleaning the data in order to remove any noise, outliers and artefacts; in this phase, several spatial filters were applied in the Cloud Compare software, such as Statistical Outlier Removal, Radius Outlier Removal or intensity values thresholds. Subsequently, in order to reduce the density of points while maintaining relevant topological information, the PC was subsampled. These strategies help improve the manageability of the cloud and prepare it for subsequent modelling phases. In particular, the methods used for resampling are Voxel Grid and Poisson-disk. The first method made it possible to eliminate redundancies while maintaining a step consistent with the modelling tolerance for the entire PC; in areas of greater complexity (altar, imposts and intersections of vaults, connections), the reduced-radius Poisson-disk was applied. This procedure made it possible to uniformly reduce the weight of the data where the geometry is regular and, at the same time, to maintain detail and continuity in complex areas. After the subsampling phase, it was possible to analyse the internal and external geometries, also generating a copy of the original PC, from which functional portions (e.g. central nave, pronaos, apses) were extracted for sectoral modelling of the architectural elements. This segmented approach allowed for greater efficiency in data management and geometric reconstruction. Each portion of the cloud was further analysed by generating orthogonal or oblique sections of the data, using cutting planes appropriately oriented in three-dimensional space. The sections were not generated with a single step, but rather adaptively. In fact, a regular mesh of planes orthogonal to the main axes (longitudinal, transverse, vertical) was used as the basis for the regular parts, while in the irregular or highly curved portions (altar, ribs, joints and vault imposts), the step was densified and integrated with oblique/contour sections (e.g. along arc generators/intrados or extrados). In this way, in the Cloud Compare software, it was possible to obtain more informative profiles where necessary, without increasing complexity in planar or low variability areas. The aim of this last phase was to obtain representative profiles of the architectural geometries, which could serve as a basis for surface modelling. These sections were traced using analytical curves (straight lines, arcs, splines) capable of adapting even to deformed and complex shapes, such as cross vaults, pavilion vaults, etc. Many sections were also necessary for these elements in order to fully capture the morphological variations. It was also essential to treat symmetrical geometries as independent entities, as they could have undergone deformation due to seismic events, subsidence, or infiltration. Finally, once the section curves had been acquired, they were imported into Rhinoceros software and simplified through a controlled reduction in the number of points, preserving their overall shape. These curves formed the generators of the NURBS (Non-Uniform Rational B-Splines) surfaces, which were created using a series of parameterised commands that adjusted their complexity. The surfaces obtained in this way were finished and connected to each other using merge, trim, or explode operations. In cases where the surfaces were not perfectly aligned, compensation surfaces were created, again based on the sections detected, in order to ensure geometric continuity and consistency with the survey.

IV. RESULTS

The three-dimensional modelling of the church was developed in an integrated way, including both the outer shell and the interior spaces, with the aim of faithfully reproducing the architectural features of the building.



(a)



(b)

Fig. 5. Results of 3D modelling in Rhinoceros software: main façade (a) and the interior of the church (b).

The surfaces obtained in this way were finished and connected to each other by joining, trimming or exploding operations. In cases where the surfaces were not perfectly aligned, compensation surfaces were created, again based on the sections surveyed, to ensure geometric continuity and consistency with the survey. The misalignments detected in some parts of the structure (joints) are not only due to resampling, but to a combination of factors such as registration imperfections between heterogeneous datasets and SLAM drift, pre-processing and spline approximation effects, parameterisation choices and NURBS patch subdivision, as well as occlusions and grazing angles that introduce local anisotropies. Resampling, while introducing controlled smoothing of high frequencies, has a secondary impact compared to these causes. Figure 5a shows the result of the 3D modelling and, in particular, the external architecture with the presence of other elements not strictly belonging to the church (but nevertheless attached to it), such as the icehouse and the courtyard.

Furthermore, Figure 5b shows the results of the 3D modelling of the interior of the architectural asset analysed, characterised by ribbed vaults and other architectural elements. At this stage, the elements have been carefully modelled according to their geometric complexity; this can be seen in the results of the modelling carried out for the main altar, which, due to its numerous architectural features, required a dedicated process in order to provide greater detail and quality in the representation of its constituent elements (Figures 6). The accuracy of the NURBS model was managed using a tolerance-driven criterion and verified with final checks. During the fitting phase, rational NURBS surfaces (with weights) were used to ensure the exact representation of arcs and quadrics and, where necessary, continuity constraints between patches. Adaptability was achieved through local refinement, i.e. by inserting nodes or increasing the degree only in areas with high curvature, so as to converge the error within the tolerance envelope established by the representation scale.

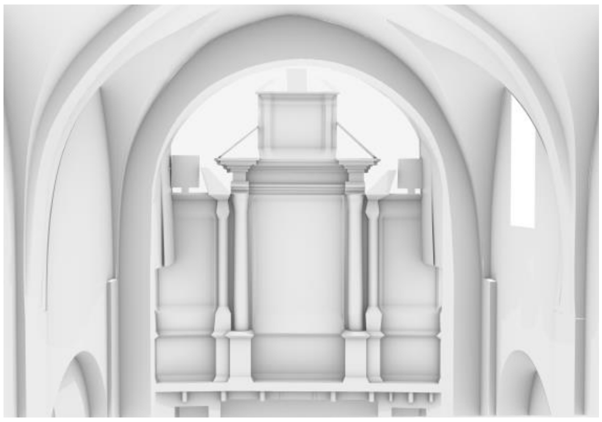


Fig. 6. Modelling of the architectural elements of the main altar.

V. CONCLUSION

The process of merging and filtering point clouds, followed by subsampling and segmentation, was essential for improving data quality and manageability while maintaining a high level of geometric detail. Through the processing of sections in Cloud Compare software and subsequent 3D modelling in Rhinoceros, it was possible to generate an accurate model consistent with the architectural reality of the analysed asset.

Nevertheless, while this approach guarantees operational speed and broad application versatility, some critical issues remain related to data heterogeneity, the complexity of registration procedures, and the management of large datasets. In fact, the 3D surveying techniques used return point clouds with different characteristics in terms of accuracy, density, and radiometric quality, making the registration and integration phase complex and requiring the use of advanced software. However, the manuscript demonstrates how these heterogeneous data have been used efficiently to obtain a 3D model capable of accurately and in detail reproducing the architectural structure of the Church of Sant'Antonio dei Cappuccini.

The adoption of rational NURBS surfaces ensured a continuous, compact and modifiable representation of historical geometries (arches, vaults, connections), avoiding the artefacts typical of polygonal modelling at the same level of detail. Furthermore, the use of NURBS made it possible to maintain the required metric accuracy while reducing complexity, post-editing time and the propagation of errors due to non-optimal discretisation. This multi-sensor approach is one of the most effective solutions for documenting and preserving cultural heritage. The combination of the two methodologies (UAV photogrammetry and handheld Laser Scanner) overcomes the limitations of each approach, ensuring complete and accurate coverage of both exterior and interior spaces, even where geometric and decorative complexity would make it difficult to use a single technique.

Furthermore, the resulting three-dimensional model, which is accurate from a metric point of view, provides faithful and complete documentation, useful for both diagnostic analysis and monitoring over time, as well as for integration into HBIM environments. In this way, it is possible to expand the potential for managing and enhancing cultural heritage by making data accessible not only to specialists, but also to institutions, administrators, and communities.

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