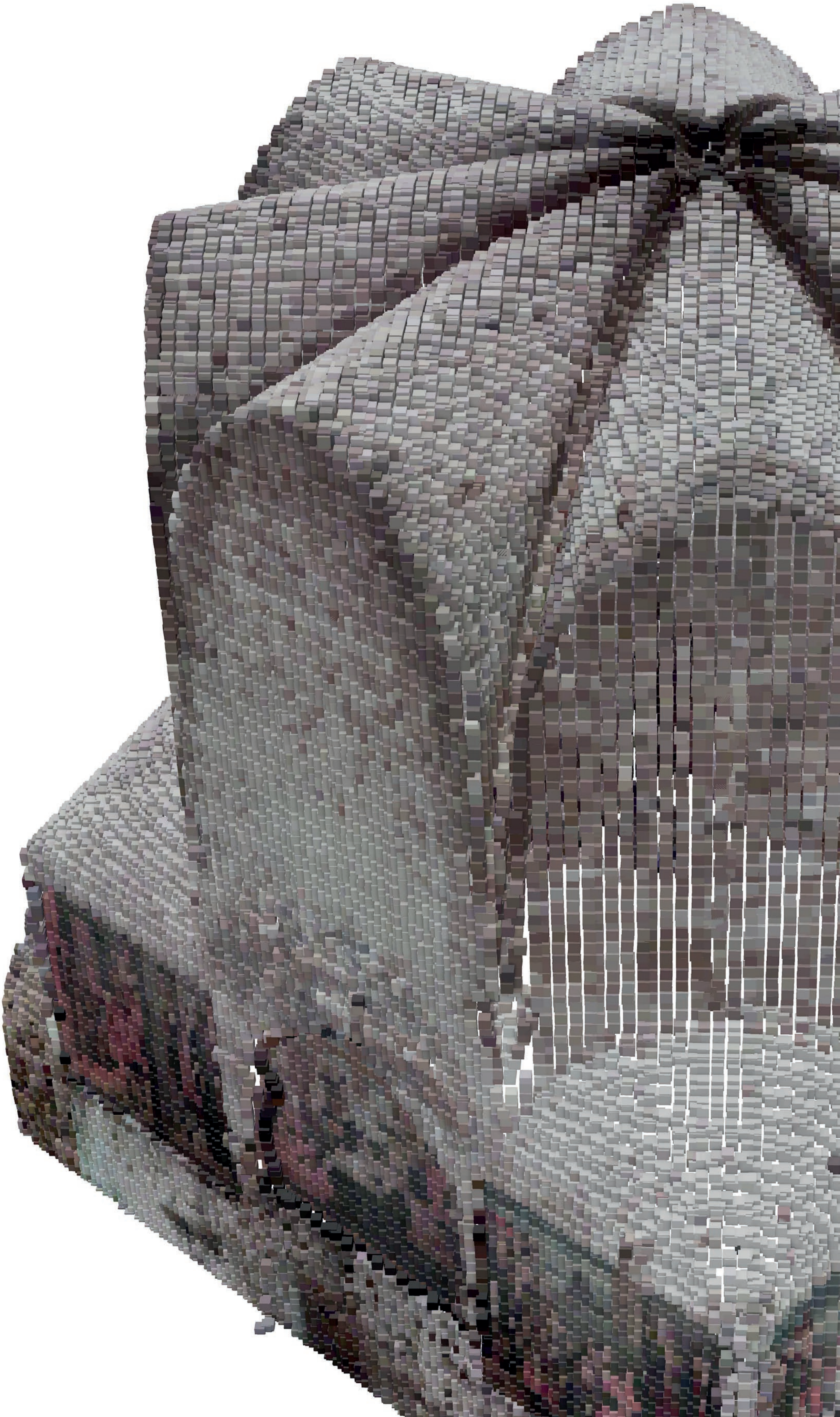

Scan-to-HBIM: automated transformation of point clouds into 3D BIM models for the digitization and preservation of historic buildings

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Abstract: Three-dimensional digital models of historical buildings must seamlessly integrate a wide array of data from diverse sources, including point clouds, alphanumeric information, 2D and 3D representations, BIM, GIS, images, sensor data, and real-time information streams, among other heterogeneous resources. Centralizing and presenting this multifaceted information cohesively is fundamental for fostering a comprehensive understanding and analysis of these historical monuments. In this context, the article introduces an automated process (Scan-to-HBIM) tailored specifically to transform point clouds into three-dimensional models within BIM environments. This innovative approach not only enhances the accuracy in representing historic buildings but also significantly amplifies the level of detail (LoD), enabling a more nuanced representation of architectural structures. The article delves into the Scan-to-HBIM process, elucidating its relevance in the broader context of digitization and preservation of historic buildings, with a particular focus on its application to a sample point cloud. Furthermore, it underscores the pivotal advantages of this approach, emphasizing its proficiency in managing diverse datasets, elevating the level of detail, and exploring practical applications in both BIM and GIS realms.

Keywords: HBIM; GIS; parametric modelling; Scan-to-BIM; cultural heritage.

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1. Introduction

Point clouds have become an invaluable resource in the historical buildings' research, providing a meticulous and accurate representation of their structure and features. These surveying technologies are crucial for initiating the analysis of a historical building and have become a vital tool in the preservation and restoration of architectural heritage (Phaedra Pocobelli et al., 2018).

In recent years, one of the most promising methodologies for digitizing information related to architecture, engineering, and construction (AEC) of historical buildings is Historic Building Information Modelling (HBIM) (Lovell et al., 2023). This methodology focuses on creating detailed digital models that not only capture the geometry of historical buildings but also their history and specific features. HBIM has become an essential tool for the sustainable preservation and restoration of heritage buildings, enabling experts to work with greater efficiency and precision in their conservation.

The implementation of HBIM enables the creation of schematic geometric models while incorporating different levels of information. This ability to combine visual representations with alphanumeric data is fundamental for understanding and managing historical buildings, providing experts with the necessary flexibility to analyse, document, and plan interventions comprehensively. Furthermore, integrating HBIM with Geographic Information Systems (GIS) extends its usefulness by extrapolating the information to a broader territorial scale, facilitating heritage planning and conservation at the local and regional levels (Banfi, 2019).

However, managing the vast amount of information generated in the study of historical buildings remains a significant challenge. The collection of detailed data through various research techniques can be overwhelming, and ensuring its organization, accessibility, and long-term usefulness is essential.

One of the fundamental challenges in this context is converting the point cloud into a Building Information Modelling (BIM) model. This transition involves transforming highly detailed data into a coherent and structured digital representation of the historical building. The accuracy and fidelity of this conversion are crucial to ensure that the BIM model accurately reflects the characteristics and geometry of the building, thereby facilitating its management and analysis. Successfully overcoming this challenge is crucial to fully leverage the advantages of BIM technology in the study and preservation of architectural heritage (López et al., 2018).

It is important to note that while the point cloud can capture an exceptional level of detail, with approximately 100,000 points/m^2 on average, BIM modelling often involves a significant simplification of the information. In some cases, the density is reduced to less than 10 points per square meter in the resulting BIM model. This simplification is necessary to effectively manage the data and ensure that the BIM model is manageable and useful in design, analysis, and management applications.

In this context, the main objective is to provide a viable and effective solution for digitizing point clouds and obtaining a wealth of information in a BIM model. The significance of this approach lies in its potential to revolutionize the modelling process of historical buildings in the realm of HBIM.

The main objective of this research is to explore and develop a methodology that maximizes the information captured by these 3D laser scanners. The potential of this technology is undeniable, but the process of converting a point cloud into a BIM model is often laborious and time-consuming. This is especially evident when dealing with historical buildings, which often present complex geometries and details.

2. Background

The study of Building Information Modelling (BIM) methodology applied to the 3D modelling and analysis of historical buildings is in constant evolution. In recent years, there has been a growing interest in its application in various fields of built heritage. We can identify an initial phase of study in which the novelty of implementing Light Detection and Ranging (LiDAR) technologies in historical objects and buildings was explored.

Currently, data capture through LiDAR has become the starting point for the study of historical structures. However, the challenge arises once we have obtained this large amount of data. The question we face is how to efficiently process this data and what products we can generate from it. In this regard, the automation of these processes has become a topic of great relevance.

In an early stage, the possibility of modelling historical buildings based on treatises and their proportions was developed. This led to the creation of a parametric library of architectural elements based on 2D information (Murphy et al., 2009; Oreni et al., 2013). In a second stage, there was the potential to model the data obtained through 3D scanning into solid three-dimensional geometries and its application

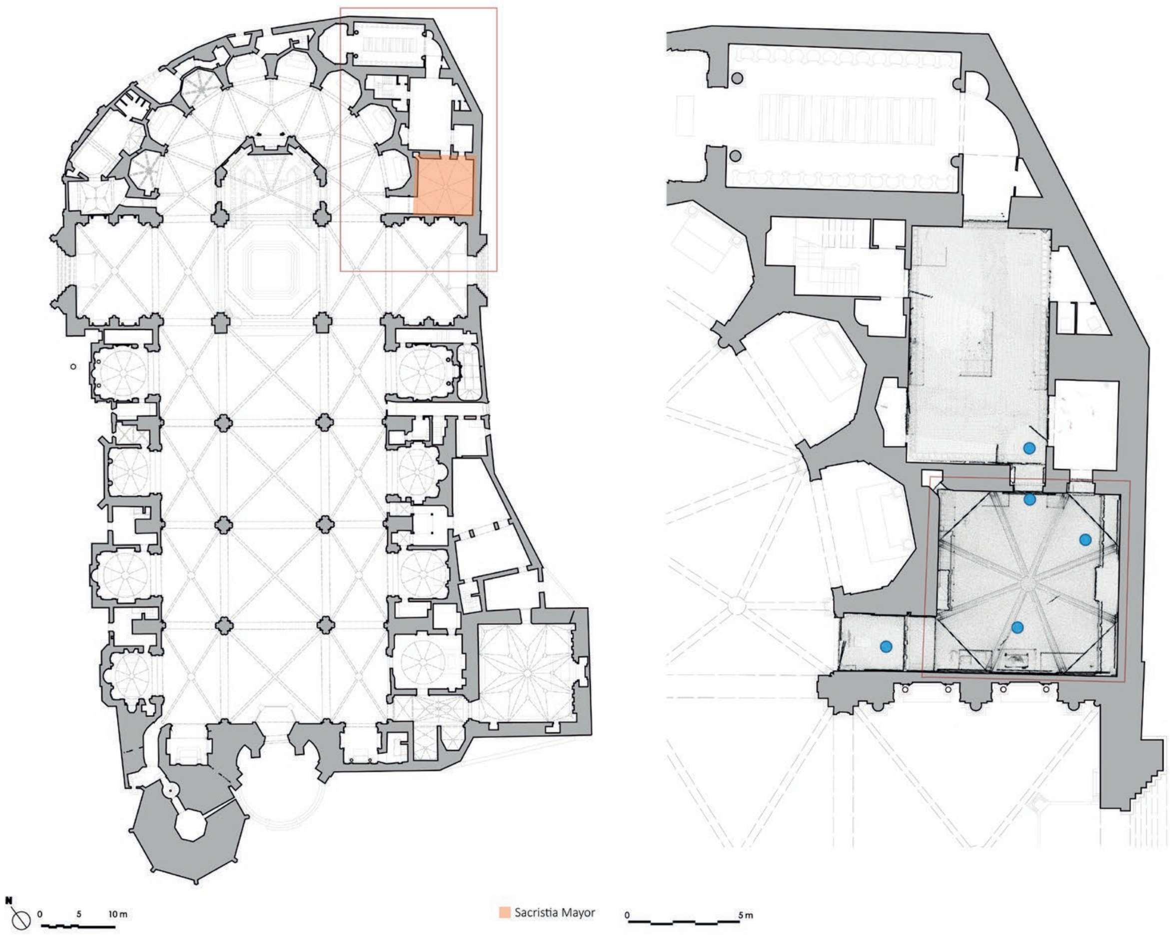

Figure 1 | Floor plan and point cloud of the sector of the Sacristy of the Metropolitan Cathedral of Valencia.

in Historic Building Information Modelling (HBIM) (Logothetis et al., 2015). Notable work was carried out in the Church of Santa Maria di Scaria (Como, Italy), where surveys were conducted using laser scanners and photogrammetry, integrating stratigraphic analysis and historical documents (Brumana, 2013). Subsequently, various studies have explored alternatives to convert point clouds into geometries compatible with the incorporation of data, especially BIM models. These research efforts have considered different approaches, such as the generation of triangulated meshes that create 2D surfaces that, when joined and closed, produce three-dimensional objects based on the use of different algorithms (Delaunay triangulation, Voronoi diagram, Ball-Pivoting algorithm, marching cubes algorithm, etc.) (Andriasyan et al., 2020). Another studied alternative was Voxelization, which involves representation using voxels with influences from video game visualization. This latter methodology has been mainly used for studying the structural behaviour of buildings based on finite element models (SfM) (Selvaggi, 2017).

The concept of BIM refers to geometric representations that include information related to Architecture, Engineering, and Construction (AEC) and are stored in a coherent database structure that enables efficient management and information exchange across different project disciplines and phases. Consequently, BIM allows for creating different levels of geometric detail according to the project's objectives. This same approach is applied to the concept of HBIM in the context of historical buildings.

Various authors have conducted in-depth research on the incorporation of point clouds into BIM models. Their studies focus on the automatic detection of surfaces, the generation of triangulated meshes between points,

Figure 2 | Point cloud containing 47,073,944 points of the Sacristy Mayor sector of the Metropolitan Cathedral of Valencia.

and other aspects related to integrating information at different levels of detail within the BIM framework. Angulo Fornos proposes the conception of a three-dimensional model and the subsequent superimposition of a point cloud to incorporate analysis data in the field of historical buildings. This approach involves generating nodes of surface information, i.e., Revit families that host all the attributes of the study element. These research efforts represent a considerable endeavour in the search for effective solutions for processing and utilizing point clouds in architectural modelling and documentation environments (Angulo-Fornos et al., 2020).

Other studies have developed a workflow for transferring point cloud data to HBIM by combining Rhinoceros®, Grasshopper, and ArchiCAD®. This methodology enables the automatic conversion of point cloud data from Terrestrial Laser Scanning (TLS) and SfM into textured three-dimensional meshes, thus creating BIM objects integrated into the HBIM project (Andriasyan et al., 2020).

In this context, there arose the need to develop a workflow that allows the conversion of the point cloud into a 3D-HBIM model. However, the aim is not to create a conventional and simplified BIM model but to go further and convert the entire point cloud into a BIM model. The goal is to obtain the maximum amount of information possible without compromising the quality of the process.

Figure 3 | Point cloud containing 7,085,550 points of the vault of the Sacristy Mayor of the Metropolitan Cathedral of Valencia.

2.1 Case Study

To achieve the proposed objective, the Sacristy of the Cathedral of Valencia has been used as a test laboratory. It possesses a rich architectural history. Built in the 13th century, it is one of the oldest and least-known spaces within the cathedral. It is located at the beginning of the ambulatory in its intersection with the transept on the epistle side. It has a square floor plan covered by a ribbed vault consisting of eight ribs inscribed within an octagon that rests on four imposts. The eight ribs that make up the vault converge at a single central keystone and are supported by trunk-pyramidal corbels. (Figure 1)

3. Methodology

3.1 Data Acquisition

The geometric complexity of the vaults in the Sacristy Mayor was a key factor in selecting this area for the study. To gather data, a 3D laser scanner was used, and data was collected from five different scanning positions. After processing, an initial point cloud of 162,069,128 points with an average error of 2 mm was obtained. To streamline the dataset, a noise reduction process was performed by isolating the area within the Sacristy Mayor while preserving the original quality (Figure 2). This resulted in a point cloud containing 47,073,944 points. Given the excessive number of points for the intended process, a second segmentation was carried out, resulting in a final point cloud with 7,085,550 points that exclusively represented the vaults (Figure 3).

3.2 Workflow

The aim of this research was to expedite and optimize the BIM modelling process of historical buildings, which often feature complex geometries and demand significantly more time compared to contemporary standardized buildings. The objective was to propose an alternative to existing methods that would also enrich the model with additional information related to the analysis and visualization of the original point cloud.

The workflow was tested using Autodesk® Revit in conjunction with the powerful visual programming tool Dynamo, designed for task automation and processing large volumes of data. The point cloud generated using TLS was exported in a standard E57 format. The cloud, which consisted of over seven million points, was imported into the open-source software Cloud Compare with the goal of converting it into an ASCII file with the ".txt" extension, which can be easily imported into Dynamo. This maintained both the integrity of the original point cloud information and the position values of each

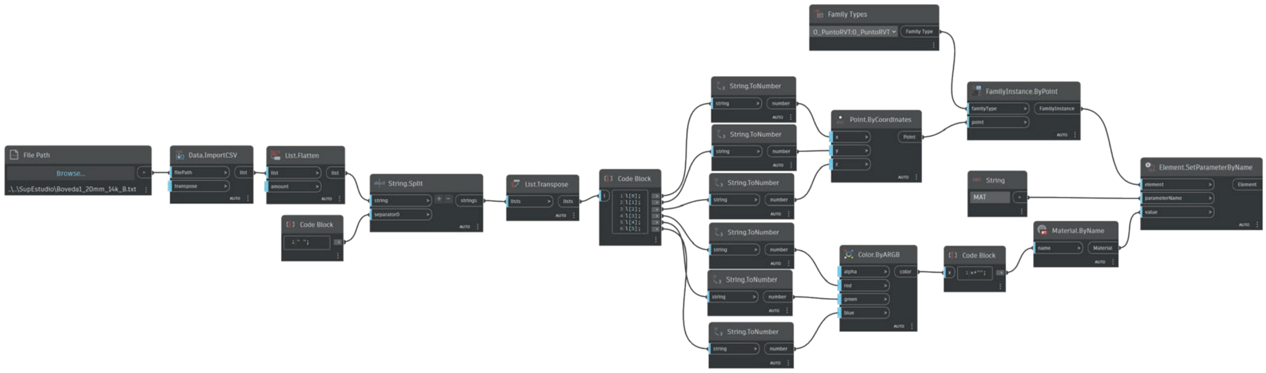

Figure 4 | Dynamo Script to Convert the Point Cloud to a BIM Model.

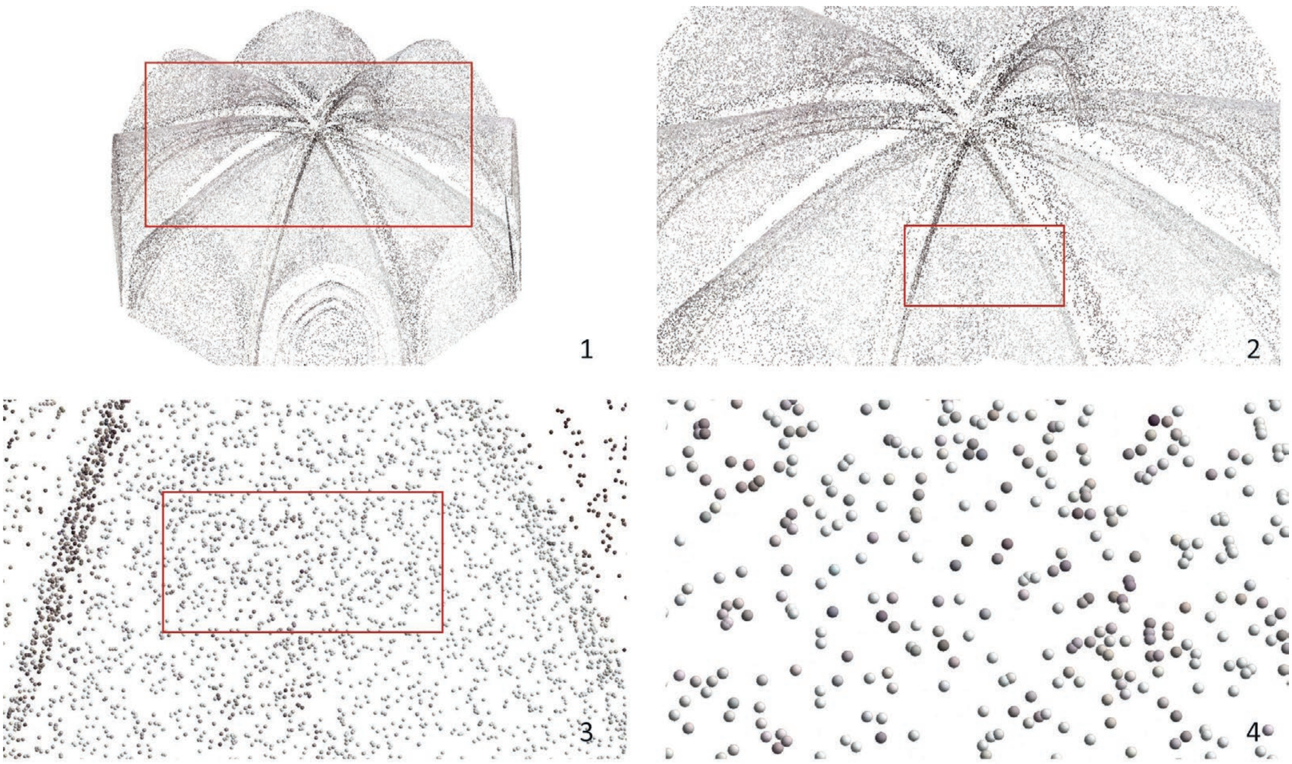

Figure 5 | Point cloud generated in Autodesk® Revit with original location and colours.

point (X, Y, Z), along with the RGB colour data captured by the scanner's camera. Additionally, it retained the normal values and attributes assigned to each point in the point cloud, which are numerical values used for point classification.

In the subsequent stage, after creating a new project in Autodesk® Revit, a basic family was designed to represent each point in 3D space geometrically. In this case, spherical shapes with a 1 mm diameter were used to represent each point, although other 3D models like cubes could also be generated for representation. This approach is based on the concept of "voxel" which refers to the smallest unit that can be represented in 3D (Foley, 1990).

To convert each point in space into a 3D geometric entity capable of containing additional information, especially relevant for historical buildings (HBIM), a routine was developed in Dynamo that imports the XYZ-format point cloud file and decomposes it into its individual values, including the X, Y, Z coordinates, RGB colour values, and all data related to different point

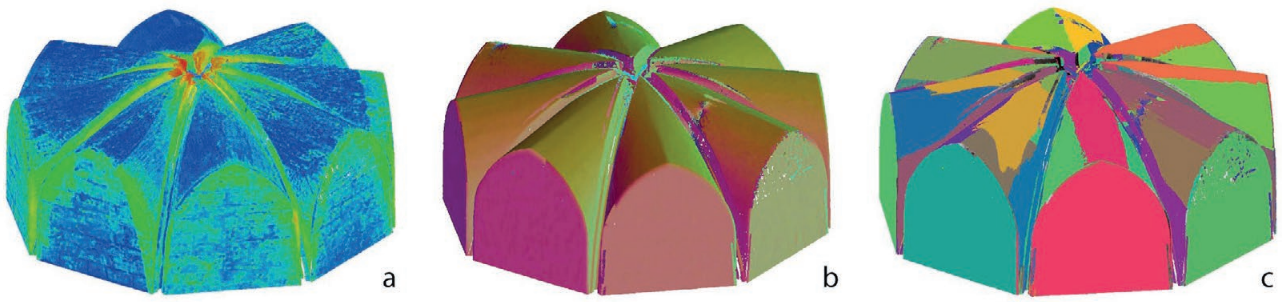

Figure 6 | Point Classification: a) Elevation b) Normal c) Plane detection using the RANSAC algorithm.

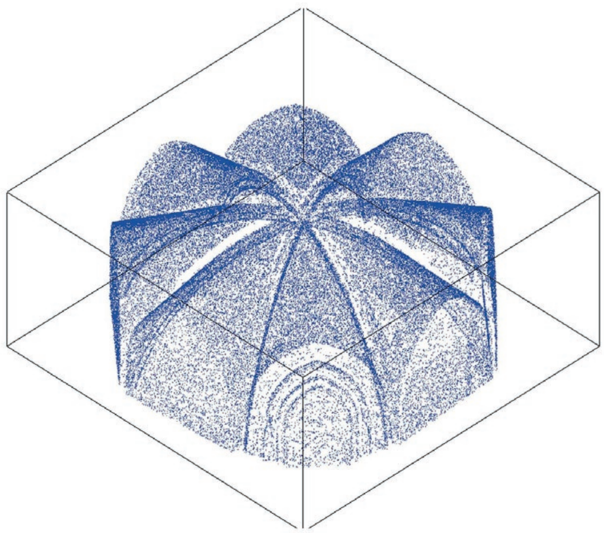

Figure 7 | 3D Model of the vault in Autodesk® Revit with 100,000 geometries.

cloud classifications. Based on these coordinates, 3D geometries were created, with each point analysed serving as the centre of gravity.

In the following phase, the RGB values were incorporated into each of the generated 3D geometries, enabling the visualization of points with their actual colours and providing a more accurate visual representation. This approach not only speeds up the historical building modelling process but also enriches the resulting BIM model with essential details and additional data necessary for the preservation and precise documentation of architectural heritage (Figure 4).

In addition to integrating RGB values, it is possible to incorporate point cloud classification information, which means different classifications of the point cloud can be generated in Cloud Compare, subsequently providing each point with the information specific to a construction element (Figure 5). In other words, each point in BIM can store data from the various scales of analysis generated, without the need to replicate the 3D geometry for each analysis layer (Figure 6). These data can be visualized through the creation of parameters using various visualization filters.

3.3 Limitations

This evaluation tested Revit's ability to process a significant volume of information, specifically seven million points, equivalent to seven million 3D geometries. Initially, samples of 50 points were taken, and as successful conversion was achieved, the quantity was gradually increased to 100, 500, 1,000, 5,000, 10,000, and 100,000 points, respectively. However, issues arose from the 5,000-point mark onward due to the additional generation of materials for representing the corresponding RGB colours. Revit became unresponsive on several occasions, and in some cases, program restarts were necessary. The maximum quantity of points with which testing was successfully carried out in a single Revit file was 100,000 (Figure 7).

These results underscore the need to segment the point cloud by constructive element and subsequently create individual files with approximately 20,000 to 40,000 points for effective information management within Revit. Additionally, the question arises regarding the limit to avoid redundancy in information. Based on the scale of the object of study and the outlined objectives, it is advisable that, for a building scale, a point distance of 0.5 m could be utilized. When analyzing a room, obtaining point intervals of 0.05 m might be interesting. In the case of specific point-like objects, such as a painting or a particular surface, maximum precision may be required, reaching point intervals as small as 0.005 m.

3.4 Utilities

This process offers several significant benefits. It enables the export of the point cloud as an IFC (Industry Foundation Classes) file, which can be visualized and imported as a

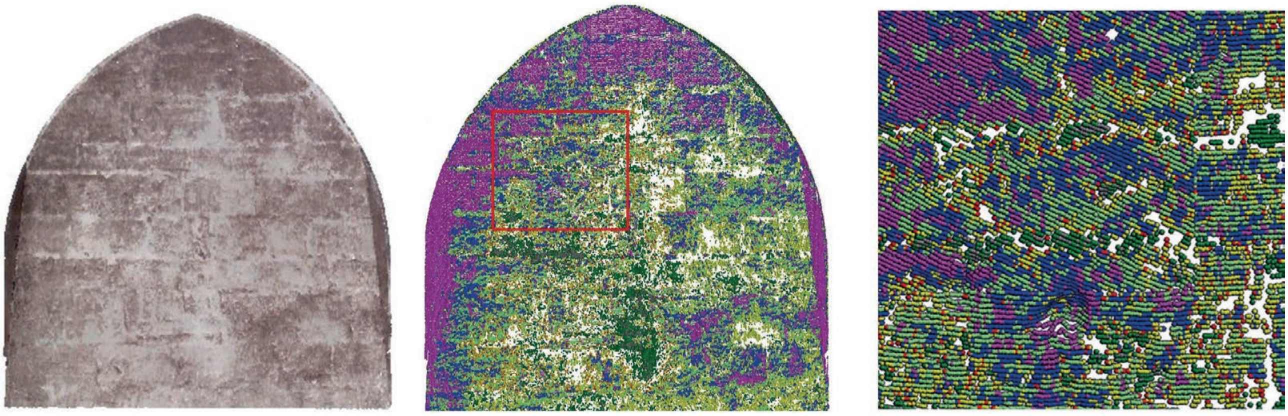

Figure 8 | Classification of the surfaces on one of the vaulted wall's 187,461 geometries based on their depth in Autodesk® Revit.

Figure 9 | Point cloud of one of the paintings in the Sacristía Mayor.

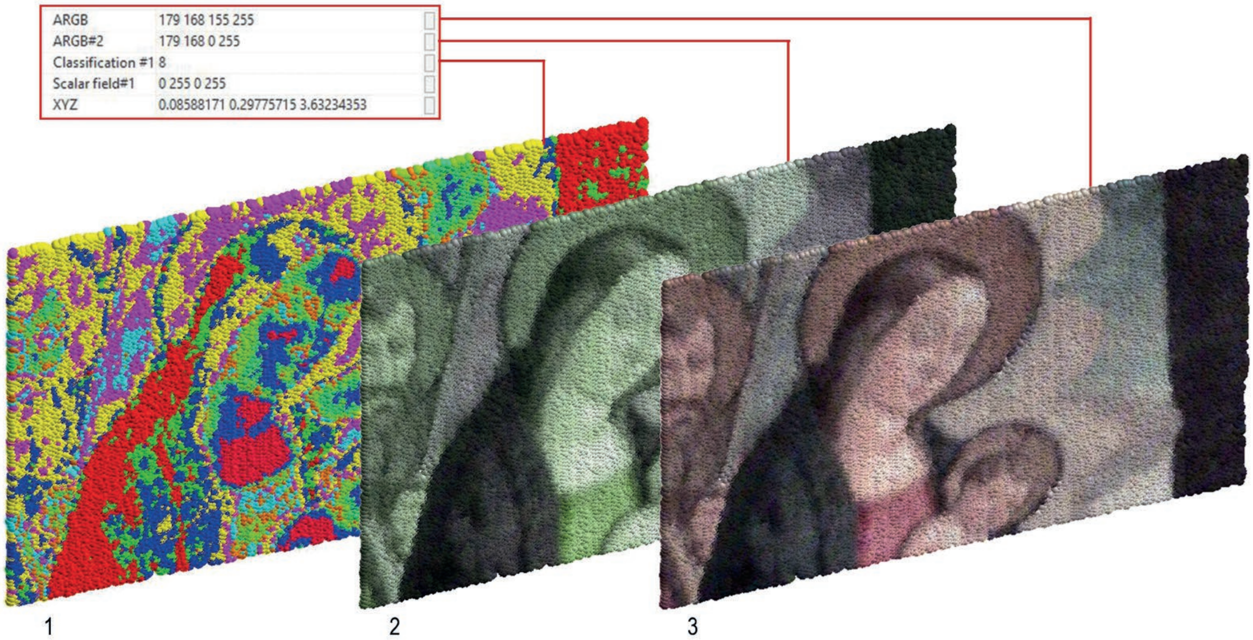

Figure 10 | Creation of a 3D BIM Model of the Sacristy Mayor Painting: 1) Classification based on similar colour tones, 2) Modified RGB, 3) Original RGB.

BIM model while preserving all of its metadata (Figure 8). Additionally, it offers the opportunity to integrate the information into a GIS (Geographic Information System) environment. The high resolution obtained is particularly interesting as it enables the inclusion of various data at each point, such as material types, pathological conditions, real-time sensor-generated information, and other possibilities.

An additional phase of this development focuses on information interoperability, with significant advancements aimed at connecting building information (BIM) with geographic information (GIS). This extends the capacity of three-dimensional digital models of cultural heritage to integrate a diversity of data from different sources, including point clouds, text data, 2D and 3D representations, images, sensor information, and real-time data, among other resources.

This methodology can also be applied to stratigraphic studies, allowing for high-resolution representation of various stratigraphic units without the need for manual 2D polygon design for each area of analysis.

Through various point cloud analysis filters, it becomes possible to identify both stratigraphic units and different types of materials used in their construction. Furthermore, each surface can be identified by incorporating parameters and subsequently exporting this information to an IFC format.

It is also possible to visualize the point cloud classifications using the values created as analysis parameters. In this particular case, an experiment was conducted on a section of one of the paintings in the Sacristía Mayor (Figure 9). The sample consisted of 19,200 points and exhibited a noticeable contrast among colours. This sample was classified using CloudCompare and imported into Autodesk® Revit through a Dynamo routine. This allowed the conversion into 3D BIM geometries and incorporated specific classification parameters, facilitating the visualization of points without the need to duplicate the 3D models (Figure 10).

Another valuable application involves incorporating the Revit model or the IFC file into a GIS system, enabling effective integration of geometry into GIS programs. Once the BIM geometry has been created, along with all the associated information for each element, exporting to GIS becomes a viable option. In this scenario, the ArcGIS Pro software has been utilized, streamlining the import process for these files.

To ensure precise visualization of the geometry and colors captured by the photographic camera, it is essential to create a parameter in BIM containing color codes. In our case, ArcGIS supports color formats in RGB, such as “rgb(255,255,0)”, or in hexadecimal, such as “#FFFF00”. This practice ensures that upon importing an IFC file, the visualization is accurate, allowing access to all information associated with each component.

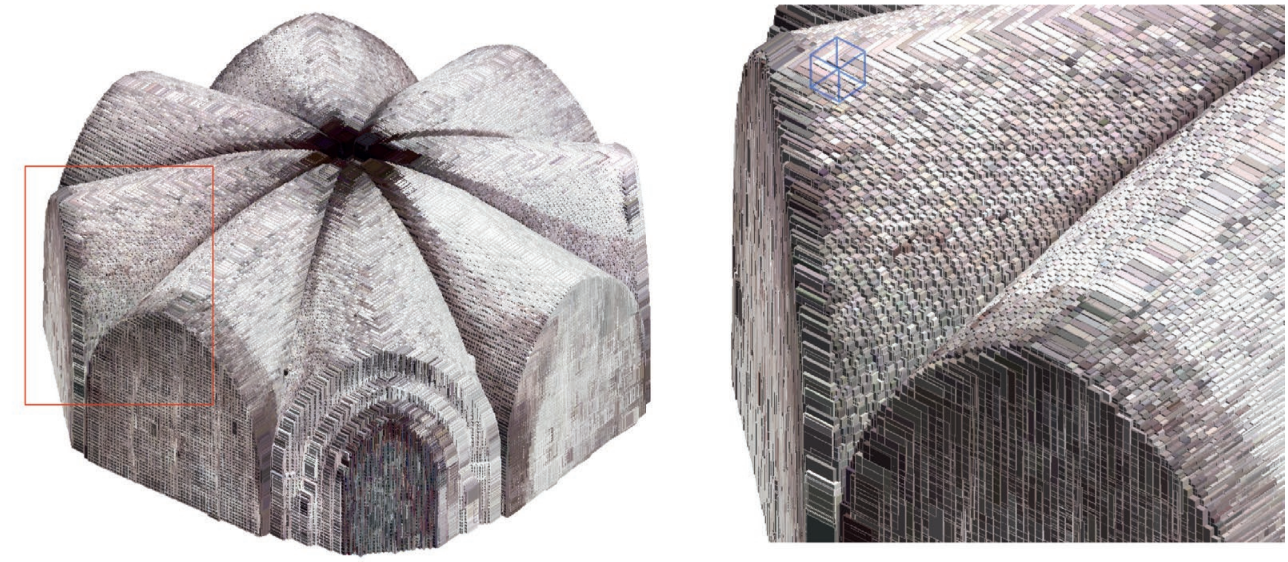

Figure 11 | Model generated in Autodesk® Revit from the point cloud of the vault.

Figure 12 | Model visualization in Esri ArcGIS Pro using the point cloud of the vault and the IFC model.

To demonstrate this, we replicated the previously developed workflow with the aim of incorporating a BIM model into a GIS platform. In this instance, a Revit model was generated from the point cloud of the vault with a point-to-point distance of 5 cm. However, for visualization, the choice was made to use a cubic-shaped Revit family (Figure 11). This resulted in a model with high resolution, where the cube size is 8 x 8 x 8 cm. Subsequently, the model was exported to IFC while retaining the original Revit characteristics and imported into Esri ArcGIS Pro (Figure 12).

To ensure the accurate visualization of the colors of the IFC model in Esri ArcGIS, it was necessary to create a Revit parameter named "rgb" with the original colors of the point cloud. This step confirms the ability to generate any type of parameter containing information that can be later utilized in GIS. Thus, achieving efficient interoperability between BIM and GIS, facilitating integrated querying and analysis of geospatial data.

Conclusions

This process becomes an essential tool for the conservation and preservation of historic buildings, as it enables experts to work with detailed and accurate data efficiently. Furthermore, the ability to incorporate a wide range of data into a BIM model further enriches the comprehensive understanding of these monuments and provides a solid foundation for informed decision-making in restoration and cultural heritage management projects.

This approach aims to simplify and optimize the conversion of point cloud data into BIM models while maintaining the integrity of the original information and providing flexibility in attribute assignment. It is expected to expedite the modelling process and enhance the quality of the results obtained.

Currently, only a few computers may have the necessary processing capacity for such extensive data volumes. However, it's just a matter of time before this capacity becomes more accessible and common, allowing smoother processing of such large-scale data.

One of the significant advantages of this methodology compared to others is its ability to preserve data integrity. It also offers the possibility to apply various analysis filters and leverage the inherent benefits of using the BIM model.

The Scan-to-HBIM process represents a significant innovation in the digitization and preservation of historical buildings by enabling the efficient conversion of point clouds into three-dimensional BIM models. Furthermore, the ability to accurately export the BIM geometry from a point cloud, along with its information and colours, to Esri ArcGIS Pro, emerges as a substantial advantage in this process. This feature broadens the analytical possibilities by integrating information into GIS programs. This methodology enhances the accuracy and level of detail of the resulting models, thereby enriching the representation of valuable architectural heritage. It facilitates the work of experts by providing detailed and precise data efficiently, supporting restoration projects and cultural heritage management.

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