3D Segmentation and Analysis for Masonry Bridge Preservation

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Abstract

In recent years, laser scanning and other survey techniques have become popular for documenting and preserving architectural and structural heritage, including masonry bridges. These bridges require careful monitoring to ensure proper structural integrity analyses. However, analysing large datasets of complex point clouds can be challenging and time consuming. This research introduces an automated method to quickly assess the geometric characteristics of vault of bridges by means of a simple algorithm purposely developed for this application. The developed methodology was implemented in MATLAB. The main geometric features, such as length, arrow, and span, are extracted, and conditional algorithms classify the vault types based on specific thresholds. The methodology is tested on surveyed masonry bridges coming from a case study: the historical Circumetnea railway bridges in Sicily, Italy. A digital survey campaign was conducted using various survey techniques such as laser scanning and photogrammetry to obtain the vault point clouds. This research represents a step forward from previous methodologies by efficiently segmenting and analysing vaults from point clouds, enabling accurate classification and geometric analysis.

1. Introduction

The preservation of masonry bridges poses a significant challenge in civil engineering, given the historical and functional importance of these assets. In comparison with steel/concrete/composite bridges, which have attracted more research interest in terms of monitoring techniques, masonry arch bridges have less frequently been the subject of specialized studies, largely due to gaps in funding and targeted research initiatives. This hinders the development of tailored preservation strategies that could otherwise benefit these critical assets.

Recent advancements in laser scanning and other expeditious surveying techniques have significantly enhanced the documentation and preservation efforts for these bridges (Trizio et al., 2021). However, these methods present challenges related to the processing of point clouds, which are computationally challenging and generally difficult to handle. Moreover, while studying bridges from an historical perspective necessitates highly detailed point clouds (Brackenbury et al., 2019; Trizio et al., 2020), there are applications in which it is necessary to expeditiously extract only certain characteristics of the structure from the point cloud (Han et al., 2023).

Additionally, extracting information from the point clouds of these structures can be demanding. Handling point cloud data require specific expertise, which is why automating these procedures for non-experts could be a step forward, simplifying the work for technicians who need basic information for quick analysis of masonry arch bridges.

Some structural analysis applications (e.g., Discrete Macro-Element Modelling (DMEM) and non-linear structural analysis) do not require detailed modelling of the bridges under study but only need certain information, which is often gathered through bridge inspections or measurements by specialized technicians. For example, the masonry bridge analysis software HISTRA (Caddemi et al., 2019) which features a parametric procedure that generates a 3D calculation model of the bridge, simply requires the geometric characteristics of the bridge as inputs. An automated procedure to obtain those characteristics would speed up the process when the data come from point clouds.

The gathering of the main geometrical characteristics of a bridge (e.g. length, span, arrow etc.) requires its semantic segmentation. In recent years, significant advancements have been made in the field of point cloud segmentation (Balado et al., 2023; Grilli et al., 2017; Lu et al., 2023; Yang et al., 2022), even through the application of machine learning and deep learning techniques and with the ultimate goal of generating accurate BIM models (Croce et al., 2021; Haznedar et al., 2023; Pan et al., 2024). These methods have demonstrated high accuracy and efficiency, leveraging complex models to handle intricate datasets.

Specifically for masonry bridges, significant efforts have been made in this direction. For instance, Jing et al. (2022) integrates 3D deep learning for point classification, surface extraction, and an improved morphological technique for space optimization.

(Brackenbury et al., 2019) discusses the development of a workflow for an automated bridge monitoring system aimed at identifying defects in masonry arch bridges using convolutional neural network (CNN) to classify various defect types based on images of masonry.

The present study proposes an automated methodology for the quick assessment of the geometrical characteristics of bridge vaults from point clouds obtained by field surveys. This MATLAB-based algorithm, while straightforward, offers several unique advantages. Firstly, its accessibility and ease of use make it an ideal tool for practitioners in smaller institutions or those without extensive technical backgrounds.

This study aims to achieve two main objectives in structural engineering through the analysis of masonry arch bridges using point cloud data: extracting key geometric information and efficiently classifying arch types.

The research builds on methodologies by (Riveiro et al., 2016) for segmenting bridge components from LiDAR point clouds and extends (Oliveira et al., 2020)'s classification framework to include a broader range of arch types.

The algorithm segmentate the point cloud to isolate the vault element. Once isolated, the vault's point cloud is oriented using Principal Component Analysis (PCA) to align it correctly in space. Subsequently, the main geometrical characteristics of the vault, are derived from the rotated point cloud.

Conditional algorithms then classify the arch type based on geometric thresholds, distinguishing between full-centred, pointed, low-centred, and multi-centred arches. Further steps of circle function fitting help differentiate between low-centred and multi-centred arches.

The algorithm is tested within a case study: the Circumetnea railway bridges in Sicily, Italy, which are significant heritage assets at increasing risk and have been extensively surveyed for both structural maintenance and cultural heritage preservation purposes. This study is part of a larger research research aimed at preserving historical masonry bridges, which are a heritage at risk (Garozzo, 2023).

The structure of the paper follows: Chapter 2 provides a comprehensive explanation of the methodological approach, beginning with an outline of the predefined objectives and then elaborating on the detailed methodological pipeline. Chapter 3 introduces the case study, offering an in-depth explanation of the Circumetnea railway and the rationale behind its selection as the focal point of this research. Chapter 4 presents the results of the study, with a detailed focus on three bridges along the Circumetnea line, highlighting key findings and insights. Finally, the paper concludes with a discussion of the conclusions drawn from the study and suggestions for future developments, indicating potential areas for further research and application.

Methodology

This study primarily aims to achieve two significant objectives within the field of structural engineering, focusing on the analysis of masonry arch bridges through point cloud data. These objectives are detailed as follows:

1. **Extraction of key geometric information**: The first goal is to obtain the main geometric features of the of the masonry arch bridge vaults, such as the arch's rise and span, as well as the width and depth of the vaults.
2. **Expeditious classification of arch types**: The second goal is to efficiently classify the type of arch that generates the vault, which is relevant for scientific investigation but also for understanding structural behaviour and potential vulnerabilities.

To achieve these goals, the research builds upon the following works. The first is Riveiro et al., 2016, which is instrumental for its methodology in segmenting masonry arch bridges into distinct structural components from LiDAR-generated point clouds. The categories segmented include pillars, spandrel walls, pathways, and vaults. Our study takes as its starting point the methodologies proposed by (Riveiro et al., 2016), focusing specifically on the "vault" element. The segmentation provided by Riveiro's approach allows for a targeted and detailed analysis of this critical structural component, facilitating the extraction of geometrical data. The second one is (Oliveira et al., 2020) which addresses the classification of arches that form vaults, offering a methodology for distinguishing between various arch types. However, Oliveira's approach was limited to semi-circular and pointed arches, excluding other arch forms. Our study extends Oliveira's classification framework by adapting it to a broader range of arch types, encompassing those typically found in rectilinear bridge structures.

Figure 1 shows the methodology flowchart whose steps are described further in the next subsections.

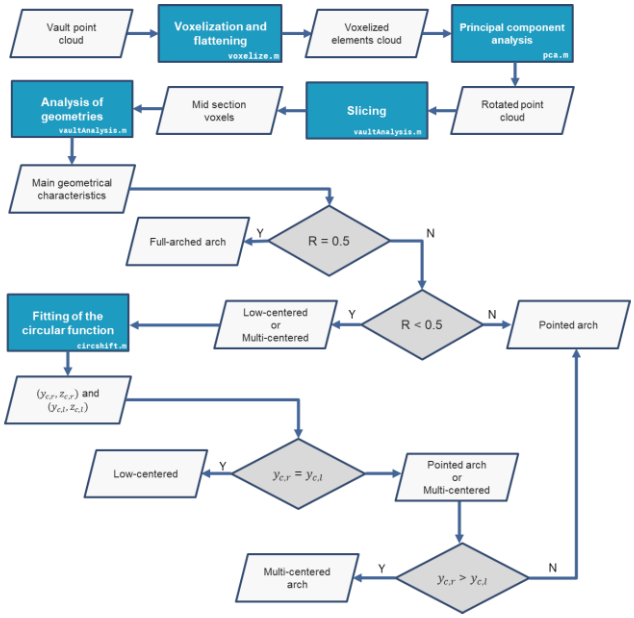

Figure 1. The methodological flowchart

1.1 Data collection

The first step of the methodology is the acquisition of point clouds of masonry arch bridges, which can be carried out with various/integrated survey techniques. This data collection is crucial as it captures the raw geometric data needed for the subsequent analysis.

1.2 Bridge point cloud segmentation and vault extraction

The collected point clouds are first segmented. This specific task involves separating the vault element from the other structural components of the bridge. Utilizing the segmentation algorithm developed by Belen et al., this process enables the precise extraction of the vault element, facilitating the further analysis. Segmentation can also be performed manually using specific software, such as Cloud Compare (CloudCompare, 2021). Therefore, in the case the isolated vault point cloud is already available, this step can be skipped.

1.3 Vault orientation

In order for information to be efficiently extracted of vaults differently oriented in space, it is essential to ensure a controlled rotation of the cloud from which to extract the information. To achieve this, it is necessary to implement a technique for rotating and aligning the cloud along its main axis. Various methodologies can be applied to do this; for this study, Principal Component Analysis (PCA) has been chosen. However, to address inaccuracies in PCA rotation due to uneven point distribution, some pre-processing steps are followed:

1.3.1 Voxelization

Voxels are three-dimensional pixels that represent values on a regular grid in three-dimensional space. The voxelization converts the point cloud into a 3D grid of voxels, which simplifies the data structure and improve the performance of PCA application.

1.3.2 Voxel grid flattening

Post voxelization, the vertical component (z) of the voxels is neutralized (set to zero) to aid in a more accurate PCA application, ensuring the vault is rotated correctly.

1.3.3 Principal Component Analysis

Finally, PCA is applied. This statistical technique is used in 3D object manipulation, such as with point clouds, to determine the primary axis associated with the largest spatial variance. This allows for accurate alignment and rotation of the vault element along its principal direction by identifying and adjusting along these principal components.

1.3.4 Voxel grid de-flattening

Once the voxelized cloud has been rotated, the vertical component is re-associated to the points, restoring the three-dimensionality of the vault and thus proceeding to the subsequent steps.

1.3.5 Identification of length and span

Once the vault longest direction is aligned along x, the algorithm identifies if this is the length of the vault or its span. In order to do so, two sections are gathered, one where $x = 0$ m and one where $y = 0$ m, Then, the variance of elevation z is computed for both sections. The section with the highest variance (the section with the highest relative difference between its points) is considered to be the span side, whereas the opposite is considered the length side. If the span is aligned along the x-direction then the vault is rotated by 90 degrees. This procedure allows for a proper sectioning of the vault, necessary for the following geometrical analysis.

1.4 Geometrical Analysis

The main geometrical characteristics of the vault are derived from the previously rotate vault, namely length (l), arrow (a), and span (s) (Fig. 2)

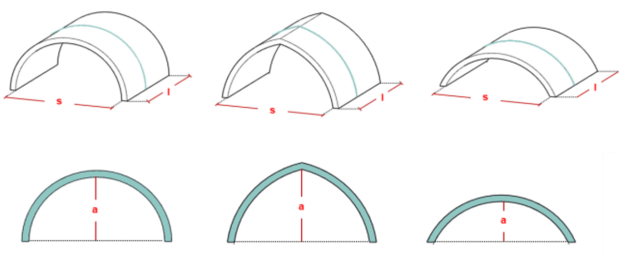

Figure 2. Main geometrical characteristic of the vault

1.5 Arch Classification

Conditional algorithms classify the vault based on specific geometric thresholds, distinguishing between lowered arch, multi-centred arch, pointed arch, and full-centred arch.

1.5.1 Classification of the typology of arch lowering

Within the proposed technique, the typology of lowering of the vault is defined through conditional algorithms. In particular, the identification is based on R, which is the ratio between arrow (a) and span (s) (a and s respectively).

If R is equal to 0,5 the arch is full-centred; if R is > 0,5 then the arch is pointed. If R < 0,5 there are two possibilities: the arch can low-centred or a poli-centred (Fig. 3). In order to identify which one of the two it is, a further step, illustrated next, is necessary.

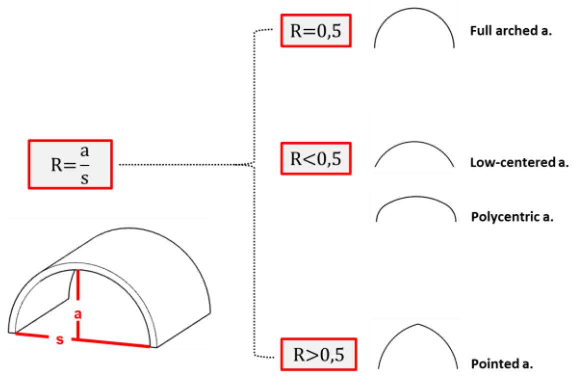

Figure 3. Classification of the type of arch based on the ratio between arrow and span (a and s)

1.5.2 Classification of the typology of arch based on centre number and position

To distinguish between a low-centred or a multi-centred arch, it is necessary to determine whether the arch is generated by a single circle (thus having only one centre) or by multiple circles (Fig. 4).

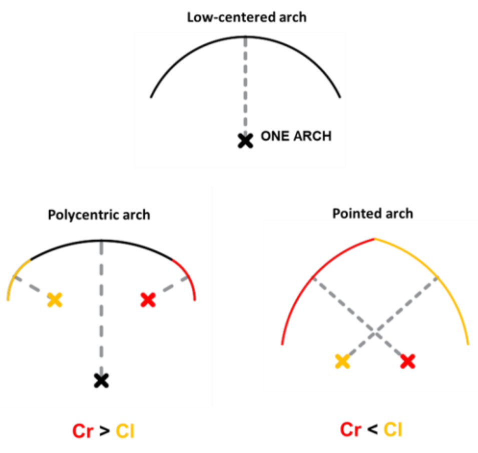

Figure 4. Classification of the typology of arch based on centre number and position

To do this, the following steps are applied:

1. The arch section previously extracted is subdivided in two semi-arches;
2. A circle fitting least-squares function is carried out to fit circles to the two semi-arches;
3. If the distance between the centres of the two fitted circles along the y coordinate is less than 0,01*l, than the arch is considered low-centred. If the distance between the two arches is greater than 0,01*l there are two possibilities:
   - If the right arch centre y coordinate ($y_{c,r}$) is greater than the left one ($y_{c,l}$), then the arch is polycentric;
   - If the $y_{c,r}$ is lesser than $y_{c,l}$ then the arch is pointed.

2. Case study

The case study for this investigation is the Circumetnea railway network's bridges (Fig. 5) in Sicily, Italy. Built between 1889 and 1895 according to 19th-century railway bridge building guidelines, these testify the authenticity of regional construction methods. Moreover, they stand out for their peculiar use of local volcanic stone, making them a distinctive feature in the local architectural landscape.
Today, these structures face growing challenges related to collapsing risk and obsolescence, prompting ongoing maintenance efforts to preserve their integrity and usability.

Figure 5. Some bridges of Circumetnea. Note, in particular, that they are heterogeneous in terms of materials, geometry, and number of arches.

The bridges exemplify the design typologies commonly employed in moderate spans (under 12 meters) for both single and multiple spans masonry arched bridges. Their construction reflects the historical and cultural *milieu* of their era, integrating well with the environment through the strategic use of local materials. These bridges are characterized by heterogeneous typologies, in terms of number of arches, materials, and geometry. Regardless of size, the bridges share consistent construction traits: arches crafted from volcanic stones or brick masonry, either fully rounded or lowered, and springings composed of uniformly-grained cut stone.
Spandrel walls are constructed from ordinary rubble masonry with either regular or mosaic facings, complemented by cut stone cantonals with ordinary grain finishes. Additionally, the pediments, walkway walls, and return walls are built using masonry that alternates between mosaic and regular facings.
In light of this, studying these structures concerns not only the reliability of the infrastructure they are part of, but also highlights their significance as iconic elements of the region's historical and cultural landscape.
A digital survey campaign was performed. The integration of several surveying methodologies, such as laser scanning, photogrammetry (ground and drone-assisted) and SLAM (Simultaneous Localization and Mapping). These techniques were required, according to the environmental conditions and the type of artefact to be surveyed. A total of 37 bridges were identified along the Circumetnea route, 11 of them were surveyed, using the abovementioned techniques. The proposed methodology was applied to three bridges, i.e. the Solicchiata bridge, the Randazzo viaduct and the Riposto bridge. These were specifically chosen to test the methodology, as they have different geometrical characteristics (i.e. R and length) and were surveyed by means of different survey techniques. Their specifics are described in the following chapter with the results of the methodology application.

3. Results

In the present chapter the results of the applied technique to the three case study bridges are illustrated.

3.1 Solicchiata bridge

The first bridge which vault was utilized to test the methodology is a small vehicular bridge located in Solicchiata, a hamlet of Castiglione di Sicilia in the province of Catania. The bridge features a single semi-circular arch made of lava stone blocks (Fig. 6).

Figure 6. The Solicchiata bridge

The bridge was surveyed using an integrated method comprising TLS (Terrestrial Laser Scanning), photogrammetry, and SLAM. However, for the methodology application, only the point cloud generated by the laser scanner was sufficient. The data acquisition was conducted using a Leica BLK360, a compact and lightweight laser scanner that captures 360,000 points per second with an accuracy of 4 mm at 10 meters and a range of up to 60 meters. The survey was performed from 13 station points. The vault point cloud, which consists of 242,541 points, was then isolated and converted into a Polygon File Format (*.ply)*.
This was the first point cloud by which the algorithm was applied, therefore it was used as a test case, providing an opportunity to assess the functionality, calibrate the algorithm parameters and make necessary adjustments before applying it to the other two case studies. Figure 7 shows how the point cloud was effectively rotated within the vault orientation stage.

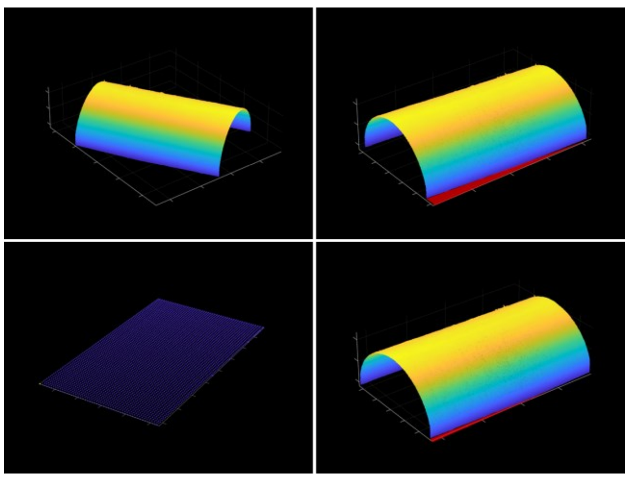

Figure 7. A) The point cloud rotated generically; B) The rotation through PCA without the flattening; C) Voxalization and flattening result; D) The correctly oriented cloud

The algorithm returned the following geometrical characteristics: a = 1.21 m, s = 2.50 m, l = 4.15 m. R is equal to 0.48 i.e. resulting in the arch being full-centred. The results of the algorithm were subsequently verified by manually measuring the geometrical characteristics of the vault using CloudCompare.

The geometrical characteristics of the vault, both measured and computed through the methodology are shown in Table 1. The comparison shows a satisfactory performance of the algorithm, with a relative difference between measured by algorithm and by survey up to +1.60%. Moreover, the algorithm correctly identified the arch as a full-centred one.

Feature	Measured by algorithm [m]	Measured by survey [m]	Difference [%]
Length (l)	4.15	4.10	+1.21%
Span (s)	2.50	2.49	+0.40%
Arrow (a)	1.21	1.23	+1.60%

Table 1. Comparison between features measured by algorithm and by survey of the Solicchiata bridge

3.2 Randazzo railway viaduct

The second bridge examined is a railway bridge that serves as an underpass for vehicles, carrying the Circumetnea tracks towards the nearby Randazzo Circumetnea station. The bridge features a segmental arch made of bricks, while the visible masonry is composed of lava stone (Fig. 8).

Figure 8. The Randazzo viaduct

Due to the heavy traffic in the area, data acquisition was performed exclusively using SLAM. Specifically, a Leica BLK2GO was used, a portable laser scanner that captures data in real-time, ensuring quickness and safety during the survey.

Once the point cloud was isolated (496,397 points), it was converted into *.ply*. The rotation of the point cloud using PCA was performed correctly, allowing the subsequent analyses to proceed (Fig. 9).

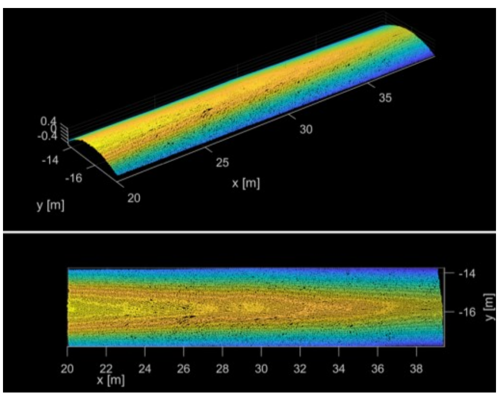

Figure 9. The rotated cloud after PCA

The algorithm returned the following geometrical characteristics: a = 0.67 m, s = 4.01 m, l = 19.47 m. R is equal to 0.17 i.e. resulting in the arch being low-centered. The geometrical characteristics of the vault, both measured computed through the methodology and their relative difference are shown in Table 2.

Feature	Measured by algorithm [m]	Measured by survey [m]	Difference [%]
Length (l)	19.47	19.38	+0.46%
Span (s)	4.01	3.96	+1.20%
Arrow (a)	0.67	0.66	+1.5%

Table 2. Comparison between features measured by algorithm and by survey of the Randazzo bridge

3.3 Riposto bridge

The last bridge analysed is a single-span one made of lava stone located in Riposto (Fig. 10).

Figure 10. The Riposto bridge

This bridge was surveyed using photogrammetry, which is suitable for a low bridge like this, particularly because its underpass, once crossed by a watercourse, is now a pedestrian crossing. Specifically, a dataset of 327 high-resolution images (4496x3000 pixels) was collected with a Nikon D5300, focal length 18 mm. These images were processed using Agisoft Metashape digital photogrammetry software. The resulting point cloud consists of 7,482,028 points. The vault point cloud, consisting of 1,333,181 points, was down-sampled with a 0.5 factor, resulting in a point cloud of 666,590 points.

Unlike the previous bridges, this one is characterized by a configuration where the span is greater than the length. Therefore, for this bridge, the algorithm rotated automatically the point cloud by 90 degrees around z axis. The result of the rotation, in this case as well, was satisfactory and allowed for the extraction of the required data (Fig. 11).

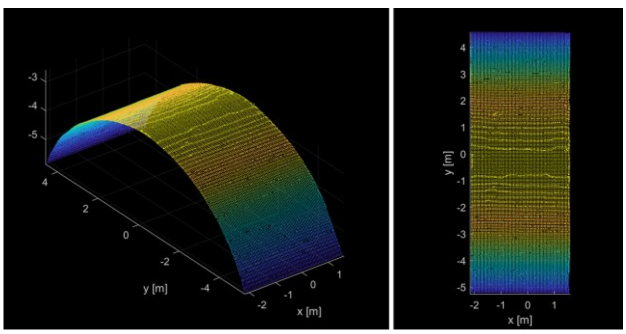

Figure 11. The rotated cloud after PCA
(Axonometric and top view)

The algorithm returned the following geometrical characteristics: a = 1.62 m, s = 9.77 m, l = 3.75 m. R is equal to 0.16 i.e. resulting in the arch being low-centred. The geometrical characteristics of the vault, both measured and computed are shown in Table 3.

Feature	Measured by algorithm [m]	Measured by survey [m]	Difference [%]
Length (l)	3.75	3.68	+1.90
Span (s)	9.77	9.79	-0.30
Arrow (a)	1.62	1.61	+0.62

Table 3. Comparison between features measured by algorithm and by survey of the Riposto bridge

4. Conclusion and future developments

In the present work, the potential of a new technique for automated identification of geometrical characteristics of masonry arch bridges from point clouds was demonstrated. The methodology involves a simple and expeditious algorithm to segmentate the bridge, align the vault point cloud along its longest direction and identify vault main geometrical features and arch type. The study was applied to a masonry arch bridge case study in Sicily, demonstrating its replication potential for other analogous applications. Future developments could involve an evolution of the algorithm to include other type of bridges, e.g. curve bridges, diagonal bridges etc.

This research aims also at contributing to architectural preservation by developing an effective procedure for characterizing the structural conditions of masonry arch bridges. By focusing on the geometric and dimensional analysis of vaults, this study offers new insights and tools for the maintenance and preservation of architectural heritage, paving the way for future applications in structural analysis and conservation practices.

The extraction procedure could also be used to speed up creation of H-BIM models, even through the use of Visual Programming Language (such as Grasshopper or Autodesk Dynamo for Revit). The work aims at representing a step forward towards the simplification of complex specialistic algorithms, enables a democratization process making advanced segmentation techniques available to a broader audience interested in the study of masonry arch bridges.

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Author contributions

Raissa Garozzo: Conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing – original draft and editing

Cettina Santagati and Belén Riveiro Rodríguez: conceptualization, supervision, project administration, writing – review and editing.

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