Collaborative defect annotation on 3D seamless open-source framework

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Abstract

Geomatics has become a critical tool for efficiently documenting the built environment, using photogrammetry, LiDAR and laser scanning to produce highly accurate 3D surveys. UAV photogrammetry enables non-intrusive documentation of heritage sites, while laser-based methods increase efficiency with millimetre accuracy. The integration of these technologies provides decision-makers with essential data for planning and conservation. However, the complexity of heritage documentation requires modular solutions capable of managing different data formats, spatial and temporal changes, while ensuring data quality and interoperability. Despite the availability of digital tools for heritage documentation, no single system seamlessly integrates all the required functionalities. Existing approaches often face challenges related to data redundancy, proprietary software limitations, and technical expertise requirements. Open-source solutions offer a viable alternative, providing low-cost, customisable tools for the presentation of thematic, 2D and 3D information. This work presents a workflow for integrating 3D survey products into a shared web-based digital platform designed to support collaborative defect mapping of built environments. The proposed framework, characterized by its open source and adaptable nature, aims to bridge the gap between research and practical applications, facilitating its adoption in diverse built heritage contexts while promoting sustainable data management practices.

1. Introduction

Over the past decade, geomatics has proven to be a valuable and time-efficient solution for documenting the conditions of the built environment. The increasing accessibility of photogrammetric techniques, often overlapping with computer vision methods, has enabled cost-effective, rapid, and accurate 3D surveys (Aicardi et al., 2019). These approaches support various applications, including documentation, analysis, and communication of cultural heritage sites. In this context, Unmanned Aerial Vehicle (UAV) photogrammetry has become an essential tool for high-resolution 3D reconstruction, allowing for non-intrusive surveys of archaeological structures while ensuring their preservation (Pepe et al., 2022). Beyond photogrammetry, 3D survey technologies such as LiDAR, terrestrial laser scanning (TLS), and SLAM offer scalable solutions based on survey needs. These methods achieve millimetre accuracy while capturing millions of points per second, significantly improving efficiency over traditional techniques (Bhatti et al., 2021). With the increasing accessibility of consumer-grade solutions, they further enhance rapid and effective heritage documentation. When combined, the high-accuracy outputs of photogrammetry and laser scanning provide decision-makers with essential data for planning and preserving urban heritage assets (De Fino et al., 2023, Fawzy, 2019).

The effective conservation and management of cultural heritage require a combined approach that integrates multiple 3D survey technologies while ensuring interoperability and sustainable data handling. Given the increasing threats posed by climate change, environmental degradation, and human activities, geoinformatics plays a critical role in both safeguarding heritage (Sustainable Development Goal (SDG) 11.4) and promoting sustainable tourism (SDG 8.9) (Xiao et al., 2018). However, the complexity of heritage documentation demands modular solutions capable of managing diverse data formats, spatial scales, and inspection epochs while maintaining data quality, metadata integrity, accessibility and adaptability (Poulopolos and Wallace, 2022). Without careful design, the proliferation of redundant datasets can lead to inefficiencies in storage and retrieval, ultimately hindering decision-making.

To address these challenges, organizations must balance internal data management needs with interoperability in broader digital infrastructures, such as spatial data infrastructures (SDIs) or digital repositories (Korro Bunuelos et al., 2021). While existing tools support specific aspects of heritage documentation from historical archiving to real-time monitoring, there is no comprehensive system that seamlessly integrates all necessary functions. Hence, a well-structured modular digital ecosystem is essential for ensuring that heritage data remains actionable, accessible, and aligned with long-term conservation goals, supporting the adoption of flexible strategies for managing a wide variety of data amount and types, looking for approaches that often fill the gap between research and practical application (Chakraborty & Ji, 2024).

For this reason, heritage building information modelling (HBIM) tools have been widely adopted in recent years due to their ability to manage multiple levels of detail (Yang et al., 2020, Aricò et al., 2024). However, they often require expensive proprietary licences and require a high level of technical expertise for implementation, interaction and querying. In this context, free and open-source options can be a valid alternative to address the issue while rendering thematic, 2D and 3D information in a cost-effective and customisable manner (Gaspari et al., 2024)

After illustrating an overview of current solutions available on the field and the potentials of adopting open-source tools, this work presents a comprehensive workflow for the integration of direct-from-survey 3D products on a shared web-based digital platform, which aims to facilitate and support collaborative defect mapping of built environments. The proposed digital framework also aims to facilitate its adoption in different built contexts, thanks to its open-source, re-adaptable nature.

2. Overview of data sharing collaborative tools

In recent decades, the literature and the Architecture, Engineering and Construction (AEC) industry have seen the proliferation of solutions for archiving, sharing and exploring 3D models. In the field of cultural heritage, a large number of customized digital management platforms, online repositories

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and web frameworks have been developed to meet the demands of professionals and researchers for handling large amounts of multimedia data, often in 3D format, for documentation and preservation purposes. Despite the specific features of each tool, the main functionalities that support an efficient workflow, especially for enhanced collaboration with teams composed of different expertise, should include interactive exploration in time and space, model and its components selection, customized scene settings and field of view, model measurements and annotations, output exports and viewer embedding in external websites (Champion & Rahaman, 2020).

The state-of-the-art of web platforms is summarized by 5 groups of solutions, distinguished based on their focus: historical storytelling and dissemination, expansion of existing data collection and processing software suites, cloud processing space, framework and standalone viewers, facility management platforms (Spettu et al., 2024). However, most of these solutions rely on proprietary software or are dependent on specific hardware, file formats, or data types.

In particular, cloud processing spaces and embedded system solutions often require a license or subscription and tend to perform best within their own closed ecosystems, which are not always aligned with open standards for geospatial data interoperability (e.g., Leica True View LIVE, Autodesk Drive, FARO Sphere Webshare, Matterport, NavVIS IVION). In addition, dedicated commercial facility management solutions (e.g. Cintoo, Bloom Explorer, Twinspect, Swiss Inspect, Nira.app), which often take a Software as a Service (SaaS) approach, have several limitations. Data is typically stored on third-party servers, raising concerns about vendor lock-in and long-term accessibility if the service is discontinued. Users are dependent on the vendor for ongoing support and updates, with little control over future pricing, feature deprecation or platform longevity. In addition, feature development is driven by the company's business priorities, which may not always align with the specific needs of users.

In contrast to proprietary solutions, the advent of WebGL (Khronos, 2009) has significantly contributed to the adoption of free and open-source technologies for web-based 3D visualization. Frameworks such as Three.js, Potree, Cesium, Babylon.js, and Giro3D have emerged as powerful tools that not only facilitate real-time rendering of 3D models but also integrate seamlessly with other open-source modules for data storage, management, and analysis (Meyer et al 2007, Rodrigues et al., 2019, Campiani et al., 2023). These technologies promote interoperability by supporting industry-standard formats for both visualization and data exchange, fostering more flexible and sustainable workflows (Rafamatanantsoa et al., 2024, Lee at al., 2024). Indeed, another issue related to the adoption of closed proprietary solution the proliferation of vast amount of different file format, often lacking proper documentation, metadata availability and interoperability strategy on the long term (Champion & Rahaman, 2020).

Moreover, open-source solutions offer a greater degree of customization, enabling users to adapt the tools to their specific needs rather than being constrained by predefined features or vendor-driven updates. These characteristics allow developers to easily define distinct modules for data and information storing and additional advanced processing built on top of other open-source solutions (Derudas et al., 2021). As a result, these frameworks not only serve as standalone viewers but also act as collaborative environments that align with modern requirements for research, documentation, and digital heritage management.

3. Methodology

The starting point of this workflow is represented by the database and the 3D viewer designed according to the needs of documentation and defect mapping of Italian bridges in compliance with the national guidelines for risk classification and management (Gaspari et al., 2023, Fascia et al., 2024). Building on previous experience, this work aims to generalise the software architecture to the broader context of built environment inspections, while ensuring a more robust and stable integration between the data archiving module (relational database) and the exploration component (3D viewer).

The proposed digital framework is developed through four key stages: requirements analysis, data collection and processing, database and platform design, and framework implementation.

The process begins with requirements analysis, which identifies user needs and defines the functionalities essential for efficient conservation defect mapping. This stage determines the specific 2D and 3D products required for comprehensive reporting and guides the subsequent development stages, as well as the properties of the entities involved in a-posteriori analysis, when experts need to efficiently access information satisfying conditions of interest through queries.

Following this, data collection and processing are carried out using geomatics techniques tailored to the scale and complexity of the site. The processed data produces high-precision point clouds, which serve as the foundational dataset for inspection and analysis. The focus then shifts to designing the relational database and web-based platform, the two core components of the framework.

The relational database acts as a central repository, storing detailed information on structural elements, routine survey data, point cloud and image metadata, and defect characteristics such as location and type. This database is designed to facilitate dynamic access to data, allowing users to interact with and update the system in real time, while managing user roles and permissions. The resulting Entity Relationship Diagram (Figure 1) is then implemented in PostgreSQL, a popular free and open-source database management system that also offers a geospatial extension, PostGIS (McKenna & PostGIS Team, 2021).

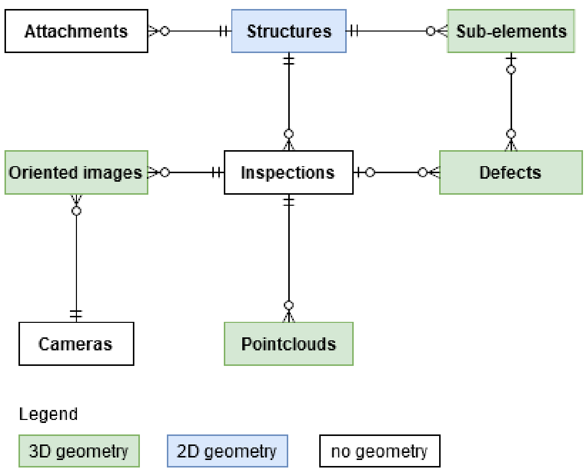

Figure 1. Entity-Relationship Diagram for inspection and documentation of built structures.

The web-based platform provides a collaborative digital space where authorized users can visualize survey assets on an interactive map, access detailed survey histories through dedicated management pages, and explore inspection products in a 3D viewer. In particular, the homepage is defined as web

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map centered on the bounding box map of the surveyed structures archived in the database. In this Leaflet.JS-based space, users can navigate the assets distribution and select a structure of interest, accessing the timeline of inspections and their associated 3D products. Indeed, if a specific survey employed the usage of UAV-cameras and/or laser scanning for 3D reconstruction, users have the opportunity to access the 3D viewer, built on top of Potree (Schütz, 2015) and Cesium libraries to render efficiently both point clouds and, if needed, basemaps and 3D tiles. The viewer can also integrate images oriented on the 3D space for enhanced usability. This combination of features enables conservation experts to annotate point clouds collaboratively, annotating visible defects directly.

Finally, the framework's implementation – named Preservation of Landmarks and Architecture through Collaborative Environment (PLACE) - emphasizes seamless integration between the database and the platform (Figure 2). This integration supports advanced capabilities such as customized data querying, sub-element management through tools like facade clipping, and compatibility with external software via direct connections (QGIS) or data export options (CloudCompare, Computer-Aided Design (CAD) Tools) for further detailed elaboration and analysis.

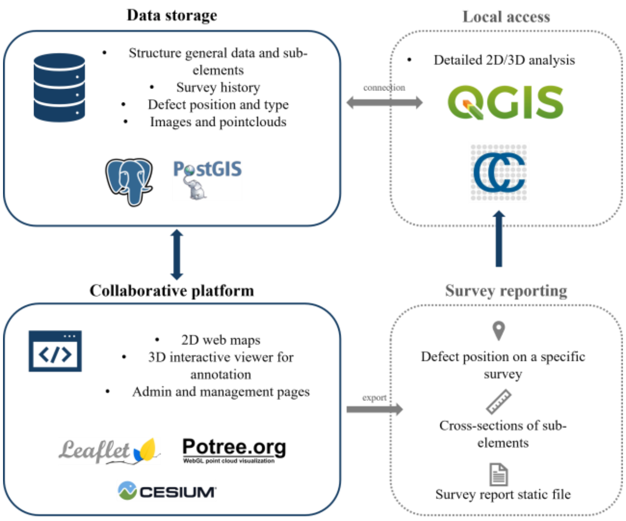

Figure 2. Overview of the proposed framework core elements and their interactions with common software for advance analysis.

4. Results and discussion

The described methodology was adopted for the digital documentation and condition assessment of the Church of the Benedictines, a 17th century Roman Catholic complex in Piacenza, Italy. The construction of the Church and its nearby monastery was completed in 1681 after four years of work, marking the subsequent entry of the nuns (Buttafuoco, 1842).

The area selected for the project is developed along the road axis connecting Palazzo Farnese with the new complex, in the northeast quadrant of the Piacenza historic center (Poli, 1999). The Church's elevation, constructed in the austere gothic style, is set on a high plinth and is rhythmically delineated by giant tuscan pilasters that culminate in a tympanum supported by an architrave, which is interrupted by an aedicule that contains the large central window, while the smaller entrance in the basement is crowned by a centering cymatium (Coccioli Mastroviti, 2007, Poli, 1999). The internal architectural elements are characterised by two adjoining liturgical spaces, the first for the public and the second for the monks, forming the so-called "double church".

A peculiar feature of the Church is the dome: supported by an octagonal tambour enriched with pilasters, statues and windows framed by tympanums, it has a lead-covered structure, which ends with a lantern. Extradosed, it represents a distinctive element in Piacenza's urban landscape.

However, although the exterior is in good condition, the interior reveals traces of the historical and functional transformations that the Church has undergone. In fact, the Benedictine order left the structure in 1810, during the Napoleonic occupation, and the deconsecrated complex came under State ownership: the monastery was converted into a barracks, while the church was used as a warehouse (Ambiveri, 1892). Even after the Napoleonic Empire fall and the end of the Second World War, the Church remained in State ownership and retained its function as a warehouse. The protection measure was formally introduced by the Ministry of Culture in March 1974, thereby subjecting the complex to the provisions of L. 1089/1939, subsequently incorporated into the Code of Cultural Heritage and Landscape (L.D. 42/2004) (Agenzia del Demanio, 2018). Over the last decades, some consolidation and restoration work has been carried out on the exterior facades and roofs, while in 2007 the entire complex was decommissioned from its governmental use. Currently in disuse, the Church shows signs of the changes it has undergone over the years: in fact, the double Church is no longer separate, but an arched opening joins the two spaces. Several of the structure's decorative elements have deteriorated, while some perforations that formerly hosted the beams that supported the mezzanines for the storage of materials are visible. Furthermore, evidence of arched structures and staircases, which are no longer extant, are clearly observable. Consequently, a mapping of the degradation present in the structure can be useful both for understanding the historical-functional transformations of the Church and for identifying the main critical points, thus providing a basis for a conscious restoration project, both from a functional and conservative point of view.

The site was surveyed using a combination of traditional topographic network surveying, UAV photogrammetry, TLS and Simultaneous Localisation and Mapping (SLAM) approaches (Figure 3). The use of the drone was essential for the reconstruction of the 43-metre-high dome, which was inaccessible using other techniques. Laser scanning was used instead for the external facades, which were only partially covered by the drone's photogrammetric cloud, as the building is located in a densely urbanised area, limiting the drone's ability to move and capture the lower part from a wider range of angles. Similarly, TLS was used extensively for the interior of the church and integrated with the SLAM point cloud created for the tightest spaces.

The external photogrammetric survey consisted of 276 images, supported by 20 control points and 7 check points, yielding a check point error of 1.7 cm. The TLS survey was conducted in two phases: the external survey included 6 scans with a registration accuracy of 0.7 cm, while the internal survey comprised 9 scans with a registration accuracy of 1.7 cm. The final alignment between the TLS and photogrammetric point clouds was achieved an overall accuracy of 0.6 cm, ensuring high geometric reliability of the integrated dataset.

The different resulting point clouds, integrated after a quality assessment by evaluating cloud-to-cloud distances, were roto-translated into a global reference system (WGS84 - UTM Zone 32 N) and divided into two distinct objects for the outdoor ($30*10^6$ points) and indoor environment ($60*10^6$ points) within a volume of 45*28*43 metres (Figure 4).

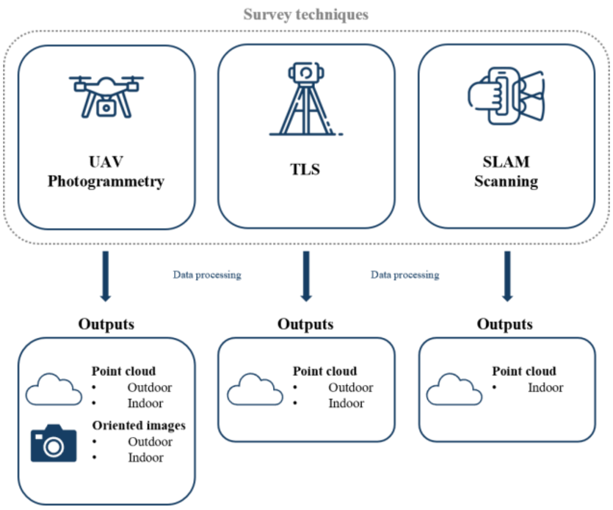

Figure 3. Schema of the surveying techniques employed for the Church of the Benedictines case study and their related outputs used in the 3D viewer.

Figure 4. Integrated outdoor scene point cloud of the case study, resulting from the co-registration of UAV-photogrammetry and TLS.

The improvements of the original PONTI project (Gaspari et al., 2023, Fascia et al., 2024), from which PLACE derives, are the flexibility in the definition of the sub-elements and the possibility to store the user interaction in the viewer. This is possible thanks to the updated design of the sub-elements entity (Figure 1), which is no longer defined a priori with a pre-processing operation on a scalar field of point clouds, but by a clipping volume operation directly inside the viewer, whose bounding box definition is stored in the database entity. Moreover, by directly linking the database to the viewer, the defects annotated on the cloud are stored directly in their corresponding entities of the database, allowing them to be reloaded in the scene in another session, as well as to be independently queried in other external software with the ability to connect to a PostgreSQL database.
The improved framework also includes the new home page (Figure 5). Indeed, the structural information and survey data that have been inserted into the appropriate tables in the relational database, completing the first steps in the implementation of the shared platform, allow the site to be visualised on a Leaflet.js web map on the platform, where detailed information on the site's survey history can also be accessed. This, together with customized basemaps of interest, can also help experts to understand the territorial context of the site, overlaying it with other external information, such as web map services of the surrounding built environment or natural hazard risk maps, also supporting a multi-scale analysis of the risk to which the site could be exposed.

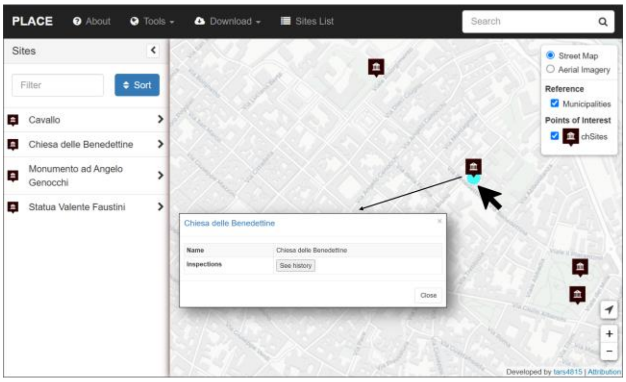

Figure 5. Homepage of the PLACE web platform with a web map the enhance a comprehensive understanding of the territorial context of a given cultural heritage site.

By selecting the heritage site of interest, it is possible to access the history of previous documented inspections with their associated assets and products, retrieved through the relationships defined at database schema level. Where point clouds are available as a result of a particular inspection in a particular time period, it is then possible to access the 3D mode. Consequently, by navigating through the Potree and Cesium-based viewer, users can begin to interactively explore the point clouds, as well as measure them and extract cross sections on specific planes of interest. In addition, if the inspection has included a photogrammetric survey, as in the case of the Benedictine Church, the 3D viewer supports the functionality of accessing the drone images, which are coherently aligned with the model as a result of the photogrammetric pre-processing that generated the point cloud. In this way, users of the platform can use the image as a support for tracing measurements or annotating visible defects (Figure 6).

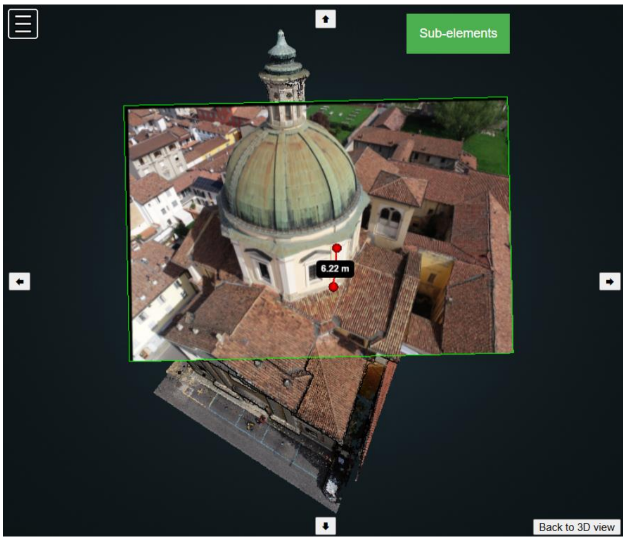

Figure 6. Exterior view of the Benedictine Church in the 3D viewer of the PLACE framework. Users in charge of assessing the conditions of a site can use this tool to support a visual a posteriori inspection, also by inspecting images oriented on the model as a result of the photogrammetric processing.

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Objects in the scene can be annotated and their labels, descriptions and coordinates stored in the database, capturing the user's interactions within annotation entities linked to the structure, its sub-elements and inspection tables. Thanks to Potree's native scene object management, it is also possible to hide or show specific elements of interest to better analyse the site.
This approach allows easy retrieval of the desired information, both from the digital platform and from any external software or tool that can connect to the database. In addition, new instances of sub-elements can be dynamically created directly within the viewer by clipping the relevant part of the scene for optimal rendering performance. These sub-elements are then given a name, making them selectable and allowing them to be associated with defects annotated within them (Figure 7).

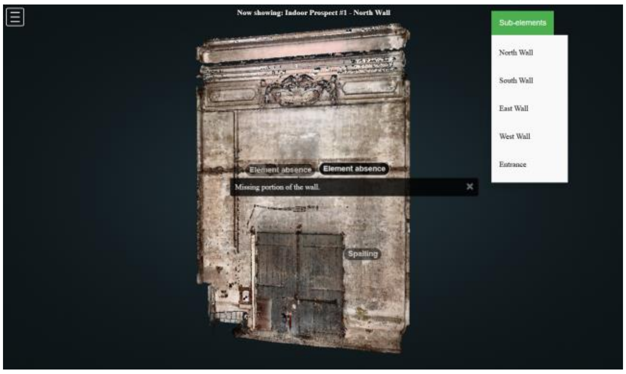

Figure 7. Interactive 3D viewer displaying defect annotations on a selected sub-element, enabling precise documentation and visualization within the point cloud environment.

A custom feature of the viewer also allows both annotations and sub-element point clouds to be exported in open formats, so that they can not only be queried via links in software such as QGIS, but also further analysed locally in advanced point cloud post-processing tools such as CloudCompare. In particular, the ability to export the point cloud of a given sub-element together with its annotated defects, load it into the CloudCompare environment (Figure 8), perform additional analysis and export orthophotos or other useful derived products to support drawing, reporting and conservation strategy planning was a useful example for this case study. Moreover, the export of sub-element point clouds is also a useful feature to support technical documentation and reporting, which can include orthophotos generated from them, as well as CAD drawings of sections along preferred planes. As a result, the platform improves defect mapping and conservation planning by integrating digital tools with traditional workflows. Typically, experts in fact produce 2D drawings with sections and orthophotos, manually mapping degradation using predefined schemes (Clini et al., 2024). This system simplifies the process by allowing in situ digital annotations, real-time documentation on mobile devices, becoming a useful tool for professional users. Moreover, the platform supports researchers who often develop HBIM models, processes that can be time and resource consuming, and dependent on proprietary authoring software. By using open-source code, the platform allows direct interaction with the point cloud as a working model, reducing the need for extensive post-processing. In addition, its open nature allows researchers to implement new functionality, fostering collaborative development and innovation in digital heritage studies.
The platform can also be used as an outreach and awareness tool: in the specific case of the Benedictine Church, which has been closed for years, it provides an accessible way to communicate the current state and potential of the building. Generally, this framework can be used for the historical and cultural dissemination of architectural heritage, monumental sites and cultural assets. By providing an interdisciplinary environment, the system in fact can encourage interaction between professionals, students and stakeholders, supporting research, education and conservation initiatives.

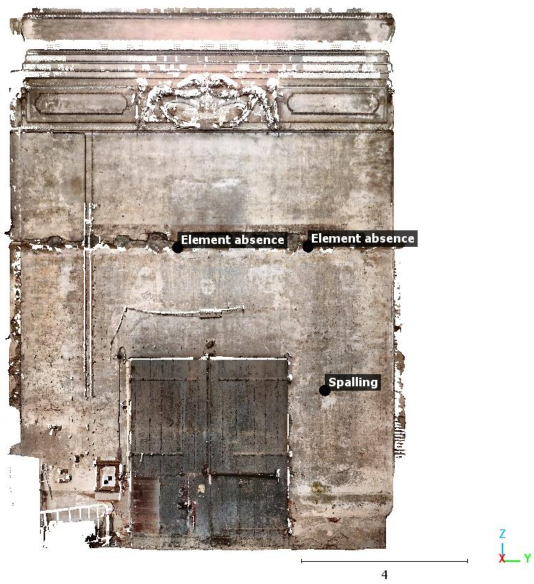

Figure 8. Exported point cloud of structural sub-element and associated annotations in the CloudCompare environment. Additional processing, meshing and rasterization can be performed to produce other products as required without having to deal with the entire point cloud.

5. Conclusions

The proposed workflow demonstrates the potential of open-source, low-code, and cost-effective solutions for integrating and managing 3D survey data on shared digital platforms. Applied to the case study, the framework has proven effective for user-friendly documentation and annotation of structural elements, linking them to detected defects and enabling seamless integration with tools such as QGIS and CloudCompare for advanced analysis. Ongoing refinements to the graphical user interface (GUI) and workflow aim to further improve usability and accessibility, ensuring the platform meets the diverse needs of its users. Additionally, user management functionalities for different expertise groups are currently being implemented to enhance collaborative workflows. Another ongoing development include the possibility of including in a single place in the viewer other format of data in support of the analysis of the built environment, such as 3D tiles for a more efficient rending and computation and Industry Foundation Classes (IFC) models from Building Information Modelling tools. As this regard, the possibility of integrating 3D models (HBIM or IFC models) will allow users to insert architectural elements, such as doors or furniture, to digitally visualise the conservation project of the architecture, providing an overview of the refunctionalized building. In addition, future implementations will consider the introduction of defect mapping through areas with different colour/texture patterns to enhance the traditional conservation process.
While the platform benefits from open-source flexibility, maintaining interoperability among integrated modules remains a key challenge, as continuous updates may introduce compatibility issues over time. To support long-term usability

and foster open collaboration, the full source code and documentation will be made available on GitHub (https://github.com/labmgf-polimi/place), encouraging contributions and innovation in cultural heritage documentation and conservation. Future testing will extend to monuments and statues, evaluating the adaptability of the framework to different heritage assets and refining its functionalities accordingly.

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