FROM 3D SURVEY TO DIGITAL REALITY OF A COMPLEX ARCHITECTURE: A DIGITAL WORKFLOW FOR CULTURAL HERITAGE PROMOTION

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ABSTRACT:

In recent years, the digitalization and dissemination of historical heritage have become crucial nodes in the preservation and valorization of Cultural Heritage (CH). Technologies such as Unmanned Aerial Vehicle (UAV) and terrestrial photogrammetry, Terrestrial Laser Scanning (TLS) and handheld Simultaneous Localisation and Mapping (SLAM) laser scanning allow the generation of digital models of architecture that can be explored through interactive web platforms, such as those based on WebGL graphic library. These are considered one of the most promising innovations for digitizing and sharing CH site due to their application in a wide range of contexts, promoting new forms of interaction with architecture at different scales. Additionally, the use of geomatic tools allows for a more complete 3D reconstruction and evaluation of the results by comparing different techniques. The article focuses on digitization as a tool for documenting and sharing CH assets, with the aim of developing a replicable prototype platform for an immersive Virtual Tour (VT) of an art collection and the architectural complex in which it is resided. In addition, this paper presents the results of a case study conducted at the Ricci Oddi Gallery of Modern Art in Piacenza, Italy. The source code of the implemented application is available on GitHub to permit replicability for other case studies.

1. INTRODUCTION

Digitization processes and dissemination strategies represent crucial aspects of research for the preservation and promotion of historical, artistic and architectural Cultural Heritage (CH). This topic has received significant support at the governmental and legislative levels, with incentives and guidelines in the Italian national context (Italian Government, 2021, MiBACT, 2019). Moreover, in recent years the scientific community demonstrated a growing interest in developing effective methods and workflows for documenting historical, architectural heritage and artistic collections (Apollonio et al., 2021, Bent et al., 2022, Tucci et al., 2017), creating digital archives and platforms that can be updated and shared between several users (Quintilla-Castán et al., 2022, Sánchez-Aparicio et al., 2020). Such processes not only facilitates the dissemination of information related to the monuments investigated, but also acts as a resource for academics, architects and conservators. Digitization simplifies the management and maintenance of historical monuments and provides support for optimising the planning and monitoring of the works analysed (Masciotta et al., 2021).
In the current scenario, the development of surveying technologies has provided new opportunities for the documentation and preservation of CH (Martino et al., 2023). Unmanned Aerial Vehicle (UAV) and terrestrial photogrammetry, Terrestrial Laser Scanner (TLS) and handheld Simultaneous Localisation and Mapping (SLAM) laser scanning are examples of such technologies that allow the creation of digital models of CH. Resulting georeferenced 3D models can be explored through interactive web-based platforms, e.g., Potree, Cesium JS or other platform based on the WebGL library (Vennarucci et al., 2021). These 3D data management platforms offer a variety of options including storage, rendering and annotation tools (Spettu et al., 2023). Advanced features, such as point cloud alignment and scan logging, permit efficient management of large amounts of 3D data without the need for specialized hardware or software (Bruno et al., 2020). Also, the development of geo-databases enables the integration of information from different sources, not only allowing the creation of specific virtual tours of architectural, archaeological and museum sites (Gaspari et al., 2023), but also promoting the digitization of CH over time. This method allows the different historical phases and changes in the heritage site to be highlighted through an immersive 3D virtual space where users can interactively experience the stories of the intangible heritage (Kocaturk et al., 2023). It promotes the exploration of regional historical and artistic heritage, and opens up new experiences by making it possible to explore places that are not always accessible to everyone for various reasons (Bordini et al., 2021, Burke et al., 2020). Such intertwining of technology and culture has led to a new paradigm that changes the way users interact with CH, providing opportunities to learn and explore history.
The purpose of this article is to illustrate a digitization-based methodology for documenting, disseminating information about and conducting web-based exploration of a complex museum architecture. Through the customised configuration of an open-source digital platform, the purpose is to facilitate both the virtual museum experience and the historical rediscovery of the context in which the collection resides. The platform chosen for this research is Potree (Schuetz, 2016), an open-source JavaScript library specialised in point cloud rendering. This platform not only provides native functionalities, such as the ability to perform measurements on the point cloud within the web environment, but also offers the possibility to insert new functionalities to support the project. The proposed

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methodology is designed to encourage the preservation and promotion of CH assets by integrating advanced surveying technologies with the digitization and online sharing of cultural content. Additionally, by providing a clear methodology for the survey phase, the article presents an example of a replicable prototype for immersive virtual tours. The methodology was applied to the case study of the Ricci Oddi Gallery of Modern Art in Piacenza, Italy. The case study aims to demonstrate the potential of this method as an effective and appealing tool for a wide range of users.

2. EXISTING VIRTUAL TOUR PLATFORMS

Virtual Tours (VT) of complex architecture and museums present an opportunity to facilitate access to and exploration of art and culture, overcoming geographical, architectural, cultural and economic barriers (Barrile et al., 2020, Germak et al., 2021, Lerario et al., 2020). Advanced imaging and virtualization technologies allow visitors to explore architecture, artworks, and information online using mobile phones, tablets, and PCs, or multiple devices such as Virtual Reality (VR) viewers and web-based Augmented Reality (AR) platforms (Banfi et al., 2021). At a time when flexibility and inclusiveness are becoming increasingly important, virtual digital tours are becoming a resource for democratising access to the riches of art and culture (García-Bustos et al., 2023), rather than supplementing or replacing physical visits.

The combination of VR and AR contributes to immersion, but a blended approach of different surveying and modelling techniques is often required to ensure high quality, realistic virtual hybrid scenarios (Gabellone, 2023). In this context, advanced technologies using multi-platform graphics engines for gaming purposes, repository software and customised WebGL graphics libraries are making their way. By exploiting output data processed after the survey phase with photogrammetry, laser scanning or mobile mapping equipment, such as images, panoramic images, point clouds and meshes, these applications create explorable virtual environments.

In recent years, various methods for designing and implementing VT have been developed, including both open source and proprietary options. Literature documents the use of proprietary software applications for the digital exploration of architectural, artistic, and cultural heritage. Immersive platforms, such as Matterport (Liu et al., 2023) and Pano2VR (Angeloni, 2023), have proven time-effective in digitizing and disseminating artistic-cultural heritage. They provide solutions for virtual visualization and interactive tours in various sectors, including architecture, tourism, and real estate. In addition, gaming graphics engines like Unity (Clini et al., 2018) and Unreal Engine (Calisi et al., 2022, Campi et al., 2022) can also serve as 3D platforms for creating immersive experiences in architecture and museums. Both VR and AR tools, such as visors and headsets, can be integrated to amplify the virtual experience, thus combining innovative and artistic aspects in the presentation of CH (Banfi et al., 2023). Although these solutions offer effective immersive experiences, they are not flexible, often expensive and complex to implement in dedicated virtual tour platforms that need to be editable and shareable. Therefore, in the field of research and democratization of knowledge, it is important to adopt open-source solutions to narrate and share CH. Open-source frameworks such as React 360 (Bakhmut et al., 2021) and A-Frame (Santos et al., 2019) have been designed to simplify the VR process by leveraging standard HTML and JavaScript technologies. Also, recent years have seen an increasing interest in the use of JavaScript libraries based on WebGL technologies in the area of CH visualization and sharing. An important example is Potree (Schuetz, 2016), which could be considered as an optimal solution for the dissemination of digitized CH and the development of digital platforms for the creation and sharing of VTs (Herrero-Tejedor et al., 2023). It facilitates the visualization of 3D products obtained by photogrammetry and laser scanning, which reproduce the surveyed structure. Specifically, the platform allows navigation and visualization in a 3D environment of various integrated products, but also includes native functionality accessible from the sidebar. Its open-source code allows for customisation and also permits users to take measurements, add annotations, oriented images and meshes, without requiring additional software packages. The justification for using Potree is based on its user-friendly interface and accessibility to a large number of users, allowing for easy exploration of the 3D model of the structure under study. This significantly contributes to the artistic and architectural appreciation of the site.

3. METHODOLOGY

The workflow proposed in this study is defined as follows (Figure 1):

1. historiographic research
2. in situ survey and 3D products processing
3. web platform implementation

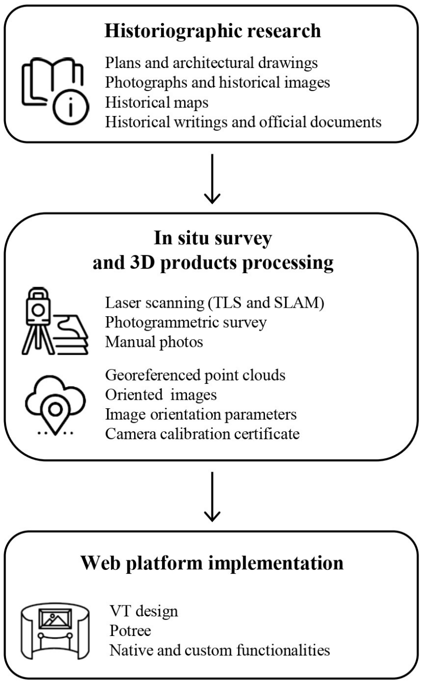

Figure 1. Workflow of the methodology and implementation of the platform.

The historiographical analysis by consulting bibliographical sources concerning the CH site and maps provides a preliminary basis for assessing its context in the urbanised area and planning the subsequent in situ investigation.

After conducting a historical analysis on bibliographical and archival documents, an on-site survey is performed both inside and outside the building using different geomatic techniques, in order to provide a complete reconstruction of the CH architecture. Firstly, a topographic network is materialised in a local reference system using a total station to obtain reference points for the subsequent co-registration of the laser scans. To

survey the exterior of the site, a UAV photogrammetric block and TLS scans are conducted. To complete the survey, a handheld SLAM laser scanner is used to take other scans of the internal rooms of the structure. These processes result in the creation of different point clouds, which must be accurately coregistered in the same global reference system. This allows for the correct integration of the various products while maintaining congruence of position and scale. Photographs of the interior architecture are manually taken to capture significant parts that are useful to acquire more information about the CH architecture. These images are also oriented in the reference system defined by the photogrammetric process in order to precisely position them on the 3D model.
The georeferenced point clouds created by the different techniques and the oriented images become the basis for developing the web platform for 3D navigation of the CH site. To implement the platform, a combination of JavaScript and HTML scripts are necessary. These codes defines the structure, aesthetics style, and functions that facilitate interaction with the elements in the 3D scene. For the case study, Potree is chosen as the platform for sharing and visualizing the results due to its open source and user-friendly nature. New features have been also integrated into the platform. A Welcome Page have been created to provide users with the necessary information to navigate the platform and create an attractive interactive environment. A search bar and information side panel have been introduced to allow users to select and view photos of the architectural interiors and access related information. This addition contributes to create a dynamic virtual space, offering users the possibility to explore independently the 3D environment. Additionally, annotations have been added to illustrate the history of the architectural complex, further improving the user experience. The platform also offers the capability to display point clouds generated by various survey tools separately, allowing users to understand and evaluate the results of the survey. The example code for the case study application is openly shared on dedicated public GitHub repositories (https://github.com/Tars4815/riccio3di).

4. THE CASE STUDY

The methodology for 3D reconstruction and digital representation was employed in the case study concerning the Ricci Oddi Gallery of Modern Art in Piacenza, Emilia Romagna, Italy (Figure 2).

Figure 2. Current state of the Ricci Oddi Modern Art Gallery and the remaining parts of the S. Siro Monastery captured during the UAV survey.

It was founded in 1931 at the request of Giuseppe Ricci Oddi, a collector from Piacenza (1869-1937), who recognised the need to move his painting collection to a more suitable and accessible location. The architecture complex was designed by the architect Giulio Ulisse Arata (1881-1962) and is situated in the southern quadrant of Piacenza's historic centre. It occupies an area between Stradone Farnese and via S. Siro, while on the other sides it is bordered by the Giordani primary school and the buildings on via S. Franca. This area has undergone several transformations over the centuries. In fact, this space was once the site of the Benedictine Monastery of S. Siro, of which only a part has been preserved.
The Gallery now holds one of the major Italian collections of 19th and early 20th century paintings and sculptures.

4.1 Historiographic research

A historical study of the site was conducted, beginning with an analysis of the land parcels previously owned by the Benedictine Monastery of San Siro. The analysis traced the historical changes from the construction to the present day, studying the maps of the Provincial Archives of Piacenza and Parma. This phase was required to understand the historical development of the site, with the aim of providing a preliminary basis for planning the following survey stage.
The Benedictine Monastery of San Siro was founded in 550 by Bishop Siro in Piacenza, making it one of the oldest in the city (Campi, 1995). In 1056, Bishop Dionigi expanded the monastery to include a dormitory, garden, cloister, and church for a community of nuns. The monastery's land holdings grew in the 12th and 13th centuries due to purchases and donations, indicating prosperity and wise administration. During the 1520s and 1527s, Abbess Lucia Bagarotti contributed to the expansion of the structure by overseeing the construction of the cloister and refectory. Later, in 1629, Count Orazio Anguissola of Podenzano carried out a complete renovation of the church and monastery. The old church was demolished in 1674, but part of the monastery remained, including two cloisters, one of which was intended for the nuns. The order was suppressed by Napoleon in 1805 and definitively closed in 1810. The complex underwent fragmentation and passed from state to private ownership, gradually disappearing in the 19th century to make way for new buildings. In fact, in 1924 the Municipality of Piacenza decided to buy the site of the former convent of San Siro, where only a few parts remained, in order to donate it to the collector Ricci Oddi for the construction of the Gallery. Ricci Oddi thus took on the responsibility not only to build the Gallery to preserve its collection and make it accessible to the public, but also to restore and connect the group of remaining old buildings to the new structure.
Giulio Ulisse Arata was chosen to design the new architectural complex linked to the existing monastic structures. The Ricci Oddi Gallery's compositional system is characterised by a longitudinal distribution system preceded by a portal and an atrium. The exhibition itinerary begins at the entrance and proceeds along the corridor, where the larger rooms are located. It ends in an octagonal space where the smaller rooms are arranged radially, defining a central plan space that opens onto the garden and surrounding area (Figure 3). Another important aspect of the new architecture is the focus on lighting (Oddi et al., 1986). The exhibition spaces were designed on a single floor with skylights in each room due to the lack of modern lighting systems at the time. This design provides optimal and uniform lighting for the artworks on display.

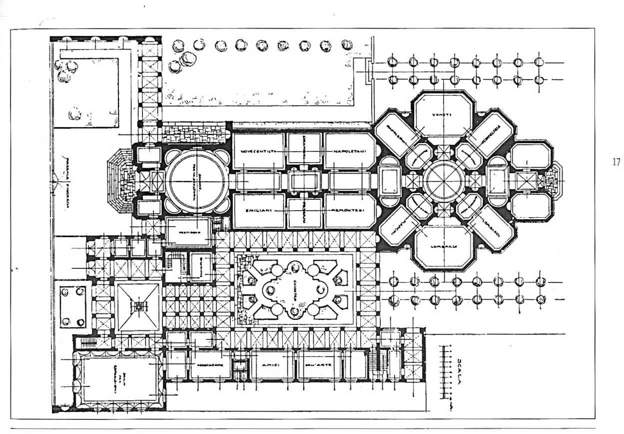

Figure 3. Plan of the Galleria Ricci Oddi, representation in *Giulio Ulisse Arata: opera completa*, by F. Mangone, 1993.

Arata's project also created a connection between the former convent and the Gallery, through a series of arcaded courtyards, some of which already existed, completed by a series of filtered passages between the various buildings. The Chiostro Grande, rebuilt on the two missing sides and opened onto the Stradone Farnese, marked the end of this link. The bricks used for the construction of the Gallery were integrated with the rest of the 17th-century monastic spaces, which were differentiated by the use of plaster.

4.2 In situ survey and 3D products processing

This phase involved the use of various geomatic techniques, including TLS, SLAM and UAV photogrammetry, to provide a complete restitution of the architectural complex.
Firstly, a topographic network was materialized in a local reference system by measuring 12 targets placed on both the architectural complex and the surrounding terrain, with a Leica MS60 Multistation. Afterwards, 4 of these targets were adopted as Ground Control Points (GCPs) for photogrammetric processing of images acquired during nadiral and oblique UAV flights, acquired with a DJI Phantom 4 RTK drone. In parallel, 23 external point cloud acquisition sessions were carried out using a Faro Focus TLS. After that, 2 scans, one interior and one exterior, were taken using a Stonex X120^{GO} SLAM handheld laser scanner. Both scans were conducted starting and ending on the same 3 GCPs that were positioned and measured at the starting moment of each SLAM survey, facilitating their mutual registration. These surveys allowed the architecture to be completely restored, both externally and internally. The SLAM surveys was carried out on a different day from the other surveys. Since the density and accuracy of a SLAM acquisition was not sufficient for high quality restitution of significant details, such as paintings, a Nikon D800 reflex camera was used to photograph the most relevant artworks. To conclude, 4 targets were measured with a GNSS antenna: this allowed the collected data to be georeferenced to the global WGS84 - UTM Zone 32 N system using a roto-translation procedure.
Images acquired through drone photogrammetric surveys were processed with Agisoft Metashape software, using a Structure from Motion approach for 3D model reconstruction (Elkhrachy, 2022). The terrestrial laser and SLAM scans were processed using dedicated proprietary software, namely Faro SCENE and Stonex GOpost respectively. Painting’s images of the Gallery collection were then oriented according to the defined reference system. After the processing phase concluded, 3 sets of point clouds were obtained: a TLS point cloud with a density of 79 million points, a UAV point cloud of 54 million points and a handheld SLAM point cloud of 65 million points, including both the internal and external survey of the structure. The quality of the point clouds was then evaluated by analysing the errors and residuals on targets not used as GCPs, but adopted as Check Points (CPs). The point clouds resulting were thus compared, evaluating the cloud-cloud distances over overlapping regions to guarantee the quality and consistency of the products. After evaluation of data quality and consistency, the point clouds were subsampled with a spacing of 2 cm..
The subsampled UAV point cloud, the TLS point cloud and the internal SLAM point cloud were processed by PotreeConverted (Schuetz, 2016) to generate an optimized octree structure suitable for rendering the in the web 3D viewer. This also allowed for a significant reduction in the amount of memory required to store the point clouds on the web server.
Similarly, the images of painting taken manually were processed and converted into .jpeg format, while their orientation and associated camera parameters were stored in separate text files. The 3 point clouds and undistorted images represent the input data for the main functionalities and basic definition of the platform.

4.3 Web platform implementation

The integrated platform combines Potree's native functions with customised features to provide an immersive virtual museum tour experience. Its functionalities are designed to simplify the exploration of the 3D digital model of the structure, allowing users to immerse themselves in the architecture and art collection through different scenarios. This was implemented through the introduction of new controls such as shortcut buttons for both the VT and the separate point cloud view, a search bar to facilitate the search for artworks and orientation images, and a pop-up side panel with text content and links to image specifications. The HTML and JavaScript code are shared on a dedicated GitHub repository, allowing interested users to easily replicate the Potree template.

4.3.1 Potree native functionalities. The ability to interactively visualise and import large datasets has allowed the integration on the new platform of the 3 point clouds obtained from the surveys. Additionally, the platform provides users with the option to customise the appearance of the point clouds by setting parameters such as colour and transparency, allowing users to explore the different products directly and intuitively (Figure 4). The platform also allows for the insertion of annotations directly in the 3D scene. This tool helps to create immersive VTs by adding notes about the history of the structure or paintings.

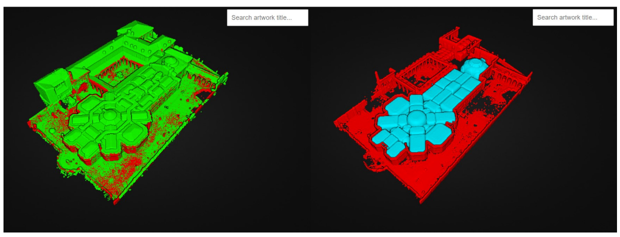

Figure 4. Custom coloured visualization of point clouds in the based-Potree platform: TLS in red, UAV in green, SLAM in blue.

4.3.2 Custom functionalities. New features have been added to the Potree platform to improve the virtual museum tour experience. The design of the Welcome Page includes a hyperlink to the museum's official website by clicking on the gallery's name (Figure 5), and displays dedicated buttons for 3D navigation of the platform, providing users with immediate and targeted directions.

Figure 5. Welcome Page of the Potree-based platform of the Ricci Oddi Gallery.

Once the web exploration is activated, users access the Potree interactive environment and its facilities. On the left side they could expand an OpenStreetMap map that provides information about the position of the site in the city of Piacenza. Additionally, a user-friendly search bar dedicated to the museum collection works present within the web platform has been included. This feature allows users to easily search for images of the paintings within the 3D model (Figure 6). Users can view photographs of the artworks, by simply searching and clicking on the name of the painting in the corresponding bar. The implementation of this feature was made possible by creating and calling a .json file, into Potree's HTML code. Such file contains important information, including the painting's title, the name of the .jpeg file that depicts the referenced artwork, and the artist's name in an array of JS objects.

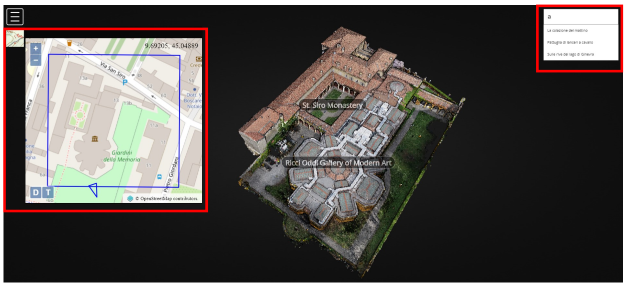

Figure 6. Main exploration page of the Potree-based platform for the VT of the Gallery. On the left: OpenStreetMap map. On the right: search bar for paintings.

After selecting the artwork, the platform automatically positions the user at the reference painting picture, allowing for immediate viewing. The image displayed is undistorted and oriented on the indoor point cloud, and the user is virtually positioned in front of the artwork, at the point where the image was taken. The images are oriented according to the relative camera exterior orientation parameters (i.e., camera location and attitude angles), estimated by a photogrammetric procedure. For each painting, the 3D coordinates of the corners of the frame were manually extracted from the point cloud and used as GCPs in Metashape to orient the image of the painting by space resection. To this end, the camera was precalibrated using a checkerboard procedure (Zhang, 2000).
Additionally, an informative lateral panel has been integrated into the platform to improve the user experience (Figure 7). The json file containing information about the artworks is linked to this, providing details such as the name of the artist, the year it was created, the materials used, and its dimensions. Additionally, a link has been included that connects the web platform to YouTube videos created by the Gallery, providing additional information about the selected work.

Figure 7. View of the interior scene of the Ricci Oddi Gallery on the Potree-based platform. On the scene, the oriented image of the painting and the info lateral panel of the artwork are visible.

5. RESULTS AND DISCUSSION

The virtualization and documentation of a complex museum architecture resulted in both qualitative evaluation of the results obtained during the surveys and the creation of a new web platform that allows visitors to experience an art collection.
The reconstruction of the Ricci Oddi Gallery had been carried out by integrating point clouds from 3 different surveys (TLS, UAV and SLAM survey). The external architecture and the convent area were acquired with TLS, due to its elevate accuracy. The roofs, on the other hand, required the use of UAV photogrammetry. The interior was surveyed with the SLAM technique, particularly effective in complex environments like the interior of the gallery, consisting of multiple rooms. SLAM laser scanner was used also to survey the external Gallery, in order to co-register both SLAM acquisitions with the TLS and UAV ones.
The TLS scans were co-registered and optimised using the ICP algorithm (Chetverikov et al., 2002), resulting in an accuracy of 2.8 cm. The UAV point cloud achieved an accuracy of 2.5 cm, evaluated as RMS over CPs. The integrated SLAM cloud, comprising of both interior and exterior clouds, was registered with the TLS cloud through a roto-translation using 9 homologous points on the ground and on the external walls. Since SLAM and TLS acquisitions were conducted on separate days, it was necessary to choose recognizable points in both 3D models, in order to use them as targets for the roto-translation, such as corners of the structure and characteristic points in the patio. The process resulted in an RMSE of 2.6 cm. Accuracy was validated in CloudCompare software by measuring the cloud-to-cloud distance between the external SLAM cloud and the TLS cloud. The differences on the overlapping parts were within 2.5 cm (Figure 8), which is comparable to the accuracy of the photogrammetric model and the TLS registration error. The use of the applied techniques would have allowed for more accurate geometric results. However, considering the aim of the project, which was to create a VT of a complex architecture, the results obtained were considered positively.
This workflow shows that the use of different instrumentation is essential to complete the survey of architecture and assess its accuracy, comparing the results of different techniques at the

processing stage to identify possible inconsistencies (Gaspari et al., 2022, Malinverni et al., 2018, Rinaudo et al., 2021, Tanduo et al., 2023). This combined approach, involving several tools, is necessary to overcome the challenges associated with the complex geometry of historic buildings such as the Gallery in question. By integrating them into a single visualization, it is possible to overcome the limitations of each technique and a complete capture of the structure achieved (Calisi et al., 2023, Ozimek et al., 2021, Perfetti et al., 2023, Pulcrano et al., 2021).

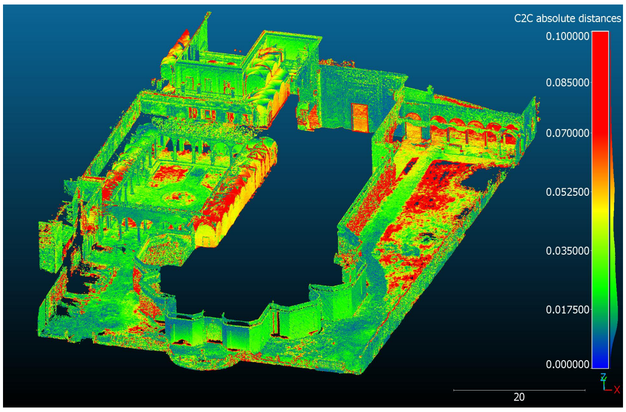

Figure 8. Cloud-to-cloud distance between the TLS and the SLAM cloud on the exterior of the gallery. In the overlapping parts, the difference does not exceed 2.5 cm. The parts in red refer to areas where vegetation growth occurred or where TLS data were missing. Values on the colour bar are in meters.

The Potree-based platform has proven to be an effective tool for digitizing CH. With a user-friendly interface, it allows a wide audience to easily explore the 3D digital model of the architectural complex and the art collection. The navigation system is intuitive and, combined with Potree's native functionality, permits the users to interact with the 3D environment without the need to install any additional software. The platform's implemented features and additional information allow the creation of a VT, making it easier to explore the Gallery and understand the architecture and artworks on display. Sharing platform code allows interested users to modify the platform or integrate new features easily, making it a versatile prototype for further deployment. This not only allows its replicability but also strengthens the foundation for the development of similar projects in different contexts.

6. CONCLUSIONS

The Ricci Oddi Gallery of Modern Art case study illustrates a methodology for digitizing architectural and artistic heritage, with the aim of developing a replicable prototype platform for an immersive and dynamic virtual tour (VT) of an architectural complex and art collection. This work also highlights how the integration of geomatics techniques and the use of open source platforms are innovating the preservation and accessibility of CH assets. The combined use of UAV photogrammetry, TLS and SLAM laser scanning facilitates the creation of 3D models for the VT, allowing accuracy assessment and survey implementation. This integration allows for immersive exploration of architecture and art collections, combining historical context with advanced technologies, and offering a complete and inclusive methodology. Open-source solution, such as Potree, can be used to create VTs using native and implemented features. This facilitates the access to CH sites and promotes collaboration and customisation of the platform. Its user-friendly interface and code accessibility allow users to modify, customize and implement the platform according to their specific project.

Future developments for the VT platform include the continuation of documentation and digitization of artworks, integration of mesh for sculptures, and the inclusion of 3D models (meshes) to represent historical objects or architectural elements that no longer exist. The aim is to implement the platform to illustrate the historical evolution of the museum's architecture. Further developments include improving the VT experience through the development of a dedicated VR version, gestural control and collaborative exploration capabilities. Advanced geospatial integration will provide a detailed geographical context of the museum, allowing for a complete immersion in the architecture and art collection.

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