Optimization of 360-based photogrammetric pipeline for narrow and dark indoor surveys

Anthony Pamart [1], Nicolas Maillard [1], Florent Comte [1], Laurent Bergerot [1]

[1] MAP, Modèles et Simulations pour l'Architecture et le Patrimoine, UPR 2002 CNRS, 13009 Marseille, France - name.surname@map.cnrs.fr

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Abstract

Photogrammetry has been commonly used for surveying architectural structures over the past two decades; however, this technique faces limitations, particularly in complex, narrow, or dark spaces due to optical constraints. Recently, advanced technologies such as 360° cameras have started to influence established photogrammetric protocols. Capturing an entire scene in a single spherical shot offers significant value for the rapid and efficient surveying of indoor spaces, although new methodologies are needed for data management, storage, and computational optimization. Building on previous work conducted within the SESAMES Project, a validated pyramidal scheme highlights the limitations of a single-camera linear sequence and emphasizes the importance of orienting "omnidirectional" sensors. This paper introduces SQUILLIDAE (Spherical acQUisition Instrument for Low-Light and InDoor nArrow spacEs), a cost-efficient and versatile multi-camera system designed to enhance photogrammetric techniques derived from spherical imagery. It details our approach from initial investigations to final design choices and includes a comparative analysis of results, as well as several perspectives for future technical improvements.

1. Introduction

Despite the recognized efficiency of close-range photogrammetry for heritage studies, this technique still faces significant challenges in complex, narrow, and low-light indoor environments. These limitations are intrinsically tied to the optical characteristics of frame cameras, though some constraints differ for omnidirectional cameras. In contrast, this study seeks to optimize the photogrammetric workflow in such challenging conditions using a cost-effective 360° and/or ultra-wide-angle (UGA) approach. The presented experiment focuses on surveying spaces under suboptimal conditions and evaluating the accuracy of their geometric reconstruction. The case study concerns several interior spaces of the Fort Saint Nicolas in Marseille, a historic monument built in 1664, which is planned to be fully restored and reopened to the public by 2030. Since certain parts of the building lack secure access and will likely remain inaccessible to people with reduced mobility (PRM), its digital survey and virtual accessibility present a significant challenge for stakeholders.

2. State of the art

2.1 Related works

Spherical photogrammetry has been a well-established practice (Fangi, 2017) for some time (Jarvis, 1948) and has been applied in various contexts, ranging from emergency documentation (d'Annibale, 2011) to condition report (Barazzetti, 2020) and dissemination purposes (Calvi, 2024). Initially a niche application, its use expanded with the development of low-cost action cameras equipped with double fisheye lenses. Since then, the scientific community has explored new ways to leverage these rapidly evolving sensors to fasten (Cera, 2022) enhance, improve, and extend photogrammetric applications (Teppati Losè; Barazzetti; Gottardi; 2018). Single- and multi-camera setups have been tested and evaluated in various conditions (Pepe, 2022; Herban, 2022; Masciotta, 2023) including experiments in videogrammetry (Sun, 2019). The effects of fisheye lenses on spatial resolution and accuracy are well-documented, providing a solid foundation for our research (Morales, 2022). Recently, multi-sensor systems (Perfetti, 2024) have been introduced to address the challenges of surveying extreme environments where conventional methods, such as close-range photogrammetry (CRP), terrestrial laser scanning (TLS), or Indoor Mobile Mapping Systems (IMMS), are either inapplicable or sub-optimal. In addition to these technical applications related to real-world modeling, alternative approaches like immersive visualization (Extended Realities, Virtual Tours, etc.) are being explored (Tejedor, 2022). One of the primary objectives of this paper is to develop a system that integrates these two types of applications.

2.2 Past and current experiments

Past research projects such as SESAMES (Blaise, 2021; Bergerot, 2022) have demonstrated that increasing the number of 360° shots taken at various optical orientations allows improved completeness of scene reconstruction with centimeter-level accuracy. However, the "pyramidal data acquisition" (i.e., opposed to strictly linear sequence) method proposed has not yet been tested in more challenging contexts. Tunnels, corridors, and other confined spaces often lack adequate lighting for photogrammetry due to limited natural light and low-intensity artificial illumination (Janiszewski, 2022). To address this issue, continuous lighting support, such as LEDs, was considered due to their high light output, long lifespan, and ability to provide soft, diffused illumination, which is ideal for 360° surveys. Additionally, designing and constructing an effective setup was necessary to maintain time efficiency during the capture phase. Nevertheless, the data workflow presents significant challenges (including panoramic reconstruction, variable lighting, and stereo pair constraints) that require optimized processing methods.

3. In-Lab : definition of the data acquisition protocol and photogrammetric processing

Technological choices were made to achieve efficient, optimized data acquisition while adhering to a "low-cost" or "cost-efficient" setup, building on the outcomes and insights of the SESAMES project. A multi-camera rig was chosen to enable simultaneous image capture from multiple positions, thereby enhancing coverage and reducing acquisition time. With the wide range of 360° camera models on the market, we selected devices that met the necessary technical specifications. Since the laboratory already possesses an Insta360 One R, we decided to continue within the Insta360 ecosystem for both hardware and software. This choice allows for synchronized captures across multiple Insta360 cameras using the Insta360 Action Remote. Consequently, the setup for this experiment includes two Insta360 One R cameras positioned at the edges of the rig, with an Insta360 X3 camera centrally mounted at an elevated position. This configuration leverages the X3's superior resolution, made possible by its larger sensor and higher megapixel count.

Specifications	Insta360 One R	Insta360 X3
Resolution (MP)	18.4	72
Sensor Size (mm)	6.16*4.62	6.4*4.8
Aperture	2	1.9
35mm Equivalent Focal Length (mm)	7.2	6.7
Run Time (minutes)	65	80
Price (€)	530	470
Release Date	2020	2022

Table 1. Specifications of the cameras' model.

3.1 Preliminary configuration and testing

Four LED panels (Manfrotto Lykos Daylight and Bi-Color, each producing approximately 1500 lux) can be oriented to illuminate the scene. While 360° lights were considered for their potential to provide uniform, diffused illumination in confined spaces, the modular LED panels proved to be versatile in practice, allowing for adjustable lighting and even enabling scenographic effects (useful for VR applications). Preliminary tests were conducted in a controlled laboratory environment to assess the setup under various configurations before in-situ deployment. Two capture configurations were evaluated: the first with two ultra-wide-angle (UGA) modules and a single omnidirectional camera, and the second using three 360° cameras. The spherical + UGA setup may be more efficient for longitudinal surveys focused on specific planes (walls, ceiling, floor), while the full panoramic configuration is expected to enhance the reconstruction of complex spaces. Ultimately, the latter method was chosen for further investigation due to its robustness and accuracy, though the first configuration may still be advantageous in certain specialized contexts.

The protocol was iteratively optimized for both capture and scaling methods to assess their effects on point-cloud generation, meshing, and texturing. The test area is a more or less parallelepiped space measuring 3.80 m in length, 1.20 m in width, and 2.5 m in height, reflecting the average dimensions of the in-situ experimental site. To simulate suboptimal capture conditions and facilitate real-world deployment, the wall surfaces were intentionally left without texture (Fig. 2). Given the spatial constraints of this lab testing area, the main parameters influencing reconstruction accuracy were, as expected, the baseline distance between cameras and the movement of the rig. However, the most significant accuracy gain was again achieved by varying the orientation of the cameras, adjusting the primary focal axis of the optical system, revalidating the pyramidal protocol. This is most probably explained by optical quality it-self correlated to extreme fish-eye radial distortion and the projection system combined with stitching artifacts (Fig.3). Evaluation was conducted using a Cloud-to-Cloud (C2C) comparison in CloudCompare (Girardeau-Montaut, 2022), referencing both control points and a dense cloud generated from a laser scan (Leica BLK2GO and S910) similarly to the method presented in section 5.

Figure 1. The SQUILLIDAE set-up mounted with a 360° cameras triplet

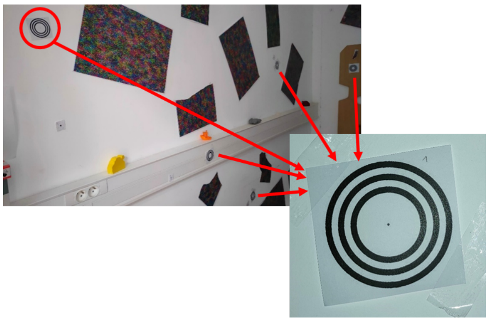

Figure 2. Test subject's wall with random patterns and CCTAG3s network.

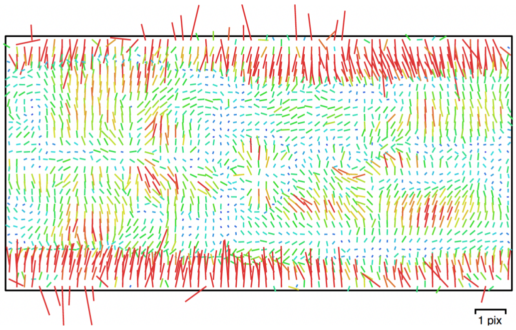

Figure 3. Exemple of image residuals for Insta360 OneR on the cells, revealing the effect of zenith and nadir distortion.

3.2 Image processing and software selection

Image pre-processing was conducted using Insta360 Studio, which handled stitching as well as leveling and feature enhancement when necessary. The camera settings were configured to capture images in DNG format, allowing for RAW processing, such as adjusting white balance or correcting exposure if needed. The testing dataset consisted of 300 images for the first setup and 800 for the second, with the difference explained by panorama decomposition, where each panorama was divided into a customizable number of single-frame images. The idea was to try different panoramic projections to evaluate their effects. A Python-based program developed in-house was used to extract a defined number of images based on a specified overlap ratio. CCTAG markers were employed for referencing and scaling the final point cloud (Fig. 2). These were chosen over other coded targets to align the workflow with open-source software like AliceVision/Meshroom.

Initially, the study aimed to compare various FLOSS solutions (AliceVision/Meshroom, MicMac) and commercial software (Agisoft Metashape, 3DZephyr) for handling panoramic photogrammetry. However, the variable input requirements for each solution proved too time-consuming, postponing this comparison. Each software has unique input constraints: Meshroom (Griwodz, 2021) processes equirectangular or single-frame images as a constrained rig, MicMac (Rupnik, 2017) requires unprocessed double-fisheye images as a rigid block (to recompose stereo pairs from dual 220° lenses), Metashape supports only stitched equirectangular images, and 3DZephyr converts them to cubic projection.

Preliminary trials revealed that while FLOSS solutions showed promise, they remained less practical compared to the robustness and speed of Metashape. Metashape was therefore selected for testing and development phases to streamline the workflow. However, further experiments with MicMac and Meshroom are planned for future evaluations.

4. In-Situ : surveys and experiments in the small confined and large underground spaces of the citadelle of marseille

The first deployment of the prototype took place in Marseille, on the south bank of the Vieux-Port, at Fort Saint Nicolas. Constructed in 1664 by the Chevalier de Clerville under the orders of Louis XIV, the fort was built to monitor the city and defend it against potential sea attacks. It was designated a Historic Monument in 1969. Since 2003, the ACTA VISTA© association has been training individuals in the restoration of the fort's ramparts and other structures. In 2021, the association *La Citadelle de Marseille* launched a 40-year project aimed at fully restoring and opening the fort to the public, transforming it into a heritage third place for concerts, exhibitions, and other cultural activities. For the first time in 2024, the Citadel will partially open to the public, granting limited access to its gardens. A full opening of the site is planned for 2030.

Figure 4. 1 : The cells of the east side. 2 : The underground tunnel of the west side. 3 : The underground tunnel of the south side.

Three areas within the Citadel were identified as particularly challenging due to documentation and accessibility issues (Fig. 4 and 6). These locations were selected for their elongated or narrow geometric shapes and poor illumination conditions. Specifically, they include former cells from the 19th century and two interconnected underground pathways, measuring 44 m and 31 m in length, respectively. A laser scan using the Leica BLK360 G2 was conducted prior to the photogrammetric survey to serve as a geometric reference and to integrate the data with other parts of the Citadel that have either been surveyed or are scheduled for future campaigns. This lightweight laser scanner is well-suited for interior modeling, provided that high precision beyond 6 mm at 10 m is not required. This paper focuses on the acquisition and processing of the cells, as this area also allows for the development of an additional application of SQUILLIDAE: its dual-purpose use for virtual reality (VR) tours (detailed in section 6).

Figure 6. Photogrammetric acquisition in the cell (left) and lasergrammetric station in the tunnel (right).

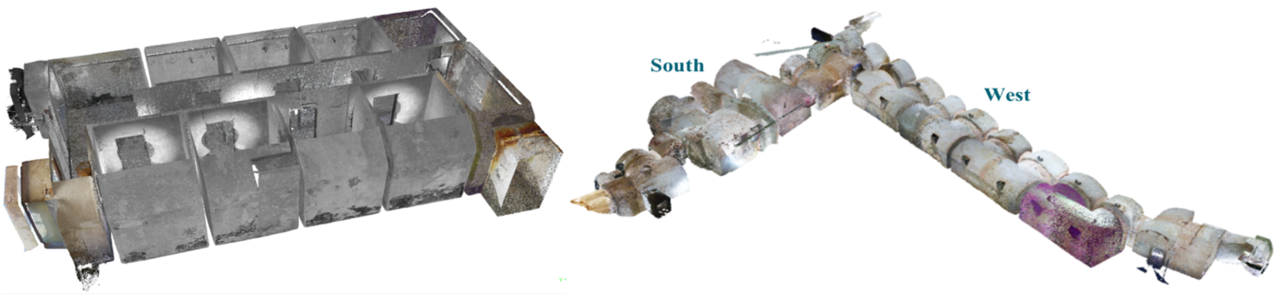

Figure 5. Point cloud from BLK360 G2, no scale defined. Left: Cells; Right: south and west underground side.

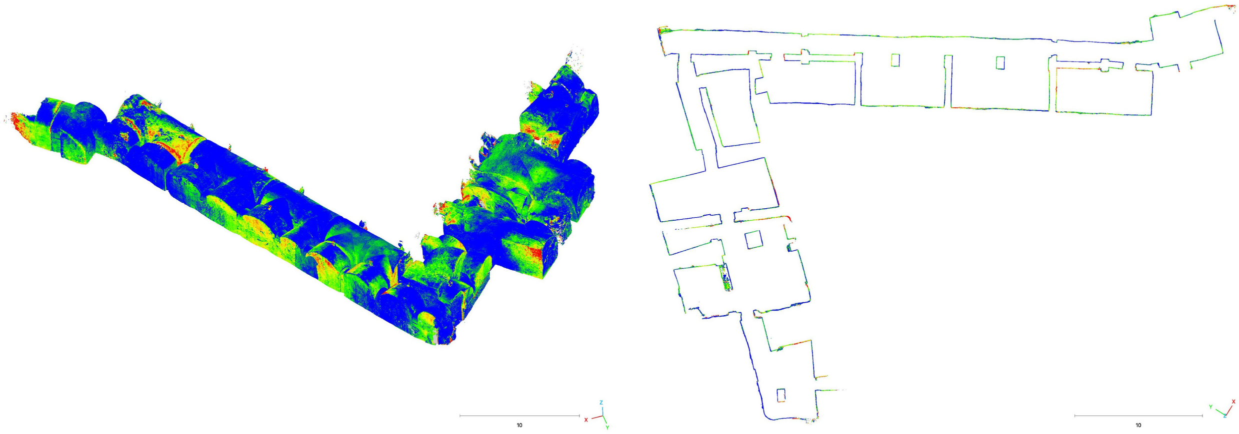

Figure7. Tunnels : left C2C discrepancy between 0 and 5 cm range in axonometric view, right plan from profile section (same range)

The in-lab protocol and setup were deployed in two complex architectural spaces. The cells consist of a small corridor leading to several pairs of small rooms, each covered with prisoner graffiti and carvings. The tunnels, composed of underground passages and adjacent vaulted rooms, presented even greater challenges for surveying, as they encompassed both linear, narrow corridors and rooms of varying sizes. The variation in illumination between the two architectural spaces remained a significant challenge, despite the use of LED panels in the prototype and an LED ribbon for the worksite. Adjusting the configuration of the LED panels proved useful in achieving uniform illumination throughout each room for every station.

The terrestrial laser scanning (TLS) survey in Fig.5 took three hours for data capture and an additional 1.5 hours for processing, generating approximately 3 GB of data. CCTag markers compatible with Meshroom were used for scaling, with a Leica S910 digital distometer employed to validate the measurements against those obtained through the photogrammetric process. A total of three hours were required to capture 415 panoramas within the cells. The baseline distance between two consecutive poses was approximately 50 cm. This distance is adaptive and can vary depending on the required precision and quality factors. In the raw image dataset, 240 pictures were taken following a specific protocol in the smaller rooms to improve dense matching. The focal axis of each spherical camera was oriented to focus on the floor, ceiling, or opposing walls, ensuring optimal optical quality for each plane. Each station was remotely triggered using a Bluetooth watch, which helped mitigate the challenge of capturing omnidirectional shots.

After completing the conventional photogrammetry workflow and exporting the point cloud, a Cloud-to-Cloud (C2C) comparison was conducted between the laser-based and image-based data sources, as discussed in the next section.

Ground Control Points		CheckPoints	
Reprojection Error (px)	Triangulation Error (m)	Reprojection Error (px)	Triangulation Error (m)
9.924	0.027	6.158	0.022

Table 2. Photogrammetric uncertainties for the cells.

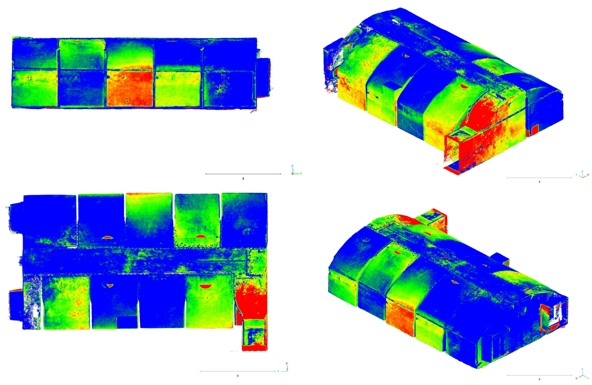

Figure 8. Cells : C2C visualization of discrepancy between 0 and 5 cm range (graphical scale). Top left : Side view. Bottom left : top view. Right top and bottom : axonometric view front and back.

5. Results and discussions

The goal was to reconstruct these complex scenes using Meshroom, but despite its integrated pipelines and features for spherical Structure from Motion (SfM), some limitations of the current version prevented the successful completion of this objective. Specifically, the setup required a double-level rig structure: one level to manage the panoramic images divided into single frames, and another to maintain the correct distances between the spherical cameras. This issue could not be resolved for technical reasons, so the remainder of the testing and validation process was carried out using Agisoft Metashape.

The cell dataset took 5 hours to process on a prosumer-grade laptop. The alignment (image matching) process alone took three hours in "High" settings due to low-light conditions and the variation in resolution between images (see Table 1). The 15 CCTAG markers were manually pointed and referenced with their local coordinates from the laser source, and 5 scale bars were added to strengthen the scaling constraints.

The table 2 quantifies the quality control measures required for validation purposes. For the scale and objectives of the survey, an uncertainty of less than 5 cm is considered suitable and acceptable for representing a wide range of architectural geometries at scales between 1:50 and 1:200. Since the goal was not to achieve metrological precision (i.e., sub-centimeter accuracy), the use of an entry-level distometer (Leica S910) and TLS (Leica BLK360 G2) met the expected accuracy and uncertainty requirements. A summary of the quality control process for control points and checkpoints is provided in Table 2. The dense matching process was completed in two hours at medium density (1pt/16 px). Higher density would have resulted in increased computational costs and a less accurate and incomplete reconstruction (required uncertainty errors [RE] should be below 4 px). The generated point cloud consists of approximately 28 million points. After removing points with confidence values between 0 and 2, the final cleaned point cloud contains around 20 million points. This cleaned point cloud serves as the basis for the comparison with the laser scan data, as detailed in the next section.

The lasergrammetric and photogrammetric point clouds were imported into CloudCompare. As the GCP coordinates from the TLS cloud were used for photogrammetric registration and scaling, the two clouds overlapped, but fine registration was still necessary, which was achieved using the Iterative Closest Point (ICP) algorithm for optimization. The CloudCompare "Cloud-to-Cloud Distance" (C2C) tool was used to calculate the distance between the two point clouds. In this analysis, the dense cloud from the 3D scanner was selected as the reference, with the TLS survey serving as the “ground truth”. The potential differences between the clouds were quantified through a neighboring analysis, which allows the observation and measurement between the two clouds. C2C was performed using the automatic method with a maximum distance set at 10 cm (i.e., points exceeding this distance were considered outliers). This approach is commonly used to directly compare two raw point clouds. The result of the comparison is expressed as a new scalar value for each point, representing the minimum and maximum distances between the two clouds. By quantifying these differences, we were also able to identify and observe areas with significant deformation in the reconstructed model.

A detailed analysis was performed to highlight the differences between the two point clouds by optimizing the color ramp. The acceptable error tolerance of 5 cm, as previously discussed, was set as the threshold (reddish color in Fig. 7 to 9). This level of uncertainty is commonly used in the scientific community to evaluate the accuracy of 3D reconstructions from spherical photogrammetry in an optimal context. The following observations were made. It is important to note that the laser point cloud for the cells contains several gaps, which slightly affected the analysis in some areas. The holes, shaped like half-disks on the ceiling, are attributed to a hardware limitation of the Leica BLK360 G2. Irregularly shaped holes on the floor and walls result from a deliberately sparse TLS network used to speed up the capture process. Despite these issues, the results are promising, showing that fewer than 7% of the 3D coordinates (20 million points) for the cells are above the 5 cm threshold, even accounting for the aforementioned suboptimal elements. For the tunnels, less than 2% of the points (40 million) are more than 5 cm from the reference. Notably, for the more challenging tunnel dataset, approximately 90% of the survey data have an accuracy of less than 3 cm when compared to the laser scan.

A summary of the results is presented in Table 3 to complete the analysis of the histogram in Fig.9 which reveals the percentage of points with relative accuracy within the 0 to 5 cm range. Points within the 2.5 cm to 5 cm range are primarily located in areas lacking clear support points, such as the entrance to the cells (Fig. 8). For instance, the first room to the left of the entrance exhibits a significant discrepancy between the ceiling and back wall, with points falling within this interval, as also shown the same figure. This difference may be attributed to high triangulation uncertainty associated with certain lack of support points.

Distance to the reference	1 cm < x	1 cm < x < 2.5 cm	2.5 cm < x < 5 cm
% of points (cells)	38	35	20
% of points (tunnels)	32	46	21

Table 3. Percentage of points falling between certain distance intervals for cells.

The combined acquisition protocol and instrumental setup demonstrated significant potential for fast and efficient surveying. The results from the prototype show that its geometric reconstruction quality is comparable to that of an entry-level laser scanner—at only a fraction of the cost, approximately 20 times less. While the laser scanner excels in acquisition speed and processing efficiency, producing smaller data volumes compared to the hundreds of gigabytes required for photogrammetric images, it comes at a much higher price. Even tough, the BLK360 G2 provides precise metric measurements without the need for scaling, yet its cost is seven times greater than the total cost of our prototype. The SQUILLIDAE setup offers flexibility, with fully demountable and adjustable components, superior color rendering for

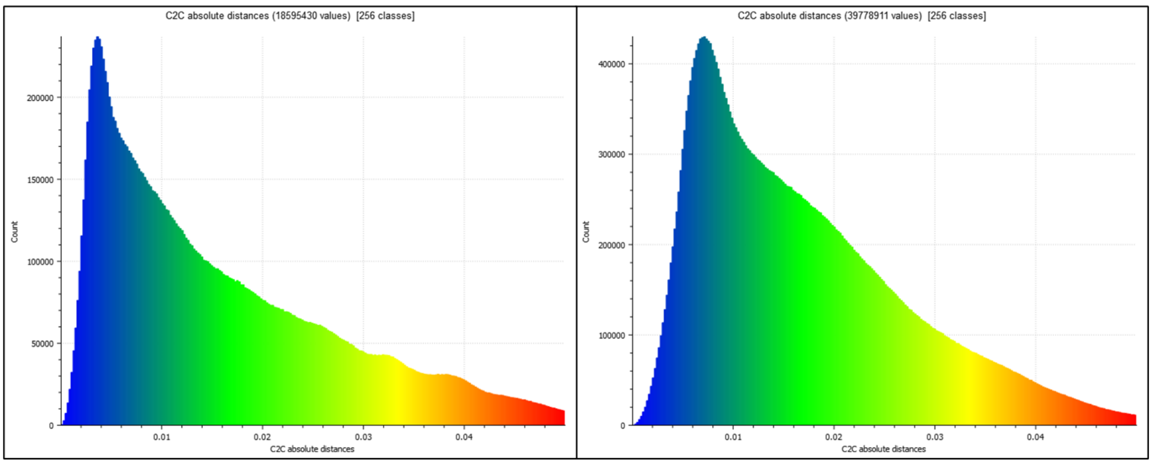

Figure 9. Results of C2C between laser-based and panoramic-based point clouds to evaluate the discrepancy between 0

texturing, and enhanced homologous point detection (improving camera internal and external calibration). This results in acceptably accurate 2D/3D representations when the target accuracy is below 5 cm.

Ultimately, each part of our system contributes efficiently to improving 2D/3D reconstruction, manipulation, and visualization. Our next goal is to develop a lightweight, multimodal acquisition system in which image-based modeling serves multiple purposes: geometric surveys, enhanced colorimetry, and VR-ready data. Given the objectives of rapid mapping and the available resources, this level of precision resulting from these first experiments is considered above than acceptable.

6. Future works and limitations

The capture achieved by the SQUILLIDAE system is also aimed at developing a multipurpose survey. The idea is to leverage the 360°-based setup to expand the prototype's capabilities, enabling the creation of Virtual Tours in addition to photogrammetric coverage, or vice versa. For this reason, the system is planned to integrate with a software prototype developed in our lab. MYRTE stands for *MY viRtual tour for archiTecture and cultural heritagE*, and shares several objectives with the instrumental approach outlined in this article. MYRTE is a free, lightweight, customizable, and scalable solution designed to create enriched virtual tours for CH applications. The application aims to empower non-IT users to create, edit, enrich, and share virtual tours that enhance the visibility and accessibility of cultural heritage monuments. To extend the functionalities of the MYRTE application, we are currently developing a multi-layer version that combines 2D and 3D exploration through point cloud integration and camera positioning. Fully automated integration is the target, but this requires further development to perfectly align the 360° panoramas and the resulting point clouds within the viewer (Fig. 10). Refining the prototype and/or acquisition protocol, alongside updating the MYRTE source code, is necessary before this combined system can reach its full potential.

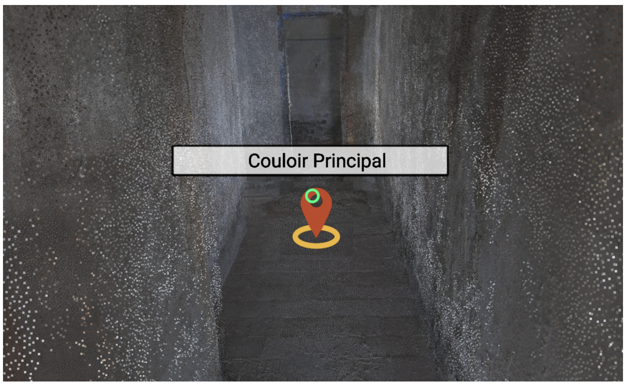

Fig. 10. First experiment of 3D overlapping with 2D images within MYRTE

This hybrid data acquisition, serving both photogrammetric-based reconstruction and VR tours simultaneously, will be the focus of future work. An updated version of the SQUILLIDAE system has been recently tested on-site, utilizing three 72 MP cameras (Insta360 X4 and X3) to achieve this objective. The limitation of low-resolution sensors for both 3D reconstruction and VR applications is overcome with this upgrade. With this setup, the triplet of high-resolution cameras enhances the photogrammetric reconstruction, while the central camera is dedicated to supporting the virtual tour aspect (eye level, consistent leveling, and orientation). Another experiment has been conducted to integrate ambisonic capture (using a Zoom H3-VR) to explore multisensory, real-time VR tours. However, a limitation inherent in using omnidirectional cameras on an instrumental rig is that the equipment itself remains visible. While this does not seem to impact the photogrammetric accuracy, it could pose problems for VR applications. During the last experiment, a calibration dataset was captured to test an AI-based masking method. If successful, further trials will be conducted to remove the operator's presence, thus eliminating the "hide and seek" issue, which is a significant limitation of shooting 360° images for cultural heritage studies or dissemination purposes.

6. Conclusion and perspectives

This experiment has expanded our research goals toward fast and efficient large-scale digitization of heritage spaces, complementing our platform dedicated to the collection of objects (Comte, 2024). We introduced the SQUILLIDAE, a low-cost instrumental solution for surveying complex architectural structures. Even under real on-site conditions, the prototype has demonstrated promising results in terms of handling, efficiency, and adaptability. The data acquired show that SQUILLIDAE is a viable alternative to entry-level 3D laser scanners, capable of reconstructing spaces in 3D and enhancing their value through virtual tours.

The ultimate goal is to develop an open system (both software and hardware) that delivers an automated workflow. Future experiments will focus on highly challenging spaces, such as revolving staircases, narrow underground areas, and complex environments like wooden frameworks (carpentry) or metal structures (factories). A promising direction also lies in the integration of AI technologies for hybrid reconstruction and visualization, currently envisioned at the intersection of Neural Radiance Fields (NeRF) approaches (Gu et al, 2022; Wang, 2024)) and extended-reality virtual tours (Zioulis, 2018) enriched with annotations and storytelling (Brumana, 2023).

Roles and contributions

Contributors: Anthony Pamart (AP), Nicolas Maillard (NM), Florent Comte (FC), Laurent Bergerot (LB), Livio De Luca (LDL).
CRediT (https://credit.niso.org/): Conceptualization : AP ; Data curation : AP, NM; Formal analysis : AP, NM, FC; Funding acquisition : AP, LDL; Investigation : AP, NM, FC, LB; Methodology : AP, FC; Project administration : AP; Resources : AP, NM, FC, LB; Software : NM, LB; Supervision : AP; Validation : AP; Visualization : AP, NM, LB; Writing – original draft : AP, NM, FC, LB; Writing – review & editing : AP.
This article has been corrected by an LLM (ChatGPT version 4) and verified by the authors.

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