SLAM-based survey supporting vulnerability assessments of built heritage at risk

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Abstract

The documentation of historical churches for structural and seismic vulnerability assessment requires survey techniques that balance metric reliability and operational efficiency. Recent developments in mobile mapping systems based on Simultaneous Localization and Mapping (SLAM) offer new opportunities for rapid and flexible data acquisition. This paper investigates the potential of SLAM-based surveys as a fast and cost-effective solution for supporting multi-level structural analyses of built heritage, adopting six historical parish churches located in the Lunigiana region (Italy) as a case study. Indoor and outdoor surveys were performed using the X70GO (Stonex), a handheld SLAM system equipped with GNSS-RTK, following acquisition strategies designed to limit drift and improve geometric consistency. The resulting 3D models are analysed primarily in relation to their usability for structural interpretation. The contribution of SLAM-derived models is discussed with reference to multiple levels of analysis, ranging from preliminary seismic vulnerability assessments based on collapse mechanisms and simplified indices to more detailed readings of structural configurations, global deformations, and damage patterns. Particular attention is also given to the practical characterization of measurement noise under typical survey conditions, in order to frame the reliability limits of geometric observations relevant to structural diagnostics. The results show that SLAM-based surveys can significantly enhance the efficiency of data acquisition and support reliable qualitative and quantitative interpretations at the building scale, especially in the early and intermediate phases of vulnerability assessment. Limitations remain in the detection and measurement of fine-scale crack patterns, which are constrained by the intrinsic noise level and spatial resolution of the system.

1. Introduction

Historic buildings require careful intervention to preserve both their formal and material aspects. Vulnerability risk assessment proceeds from preliminary analyses based primarily on direct observation and the collection of available documentary material, gradually moving towards more detailed numerical analyses that sometimes require invasive diagnostic investigations (Betti et al. 2021), such as soundings and coring, to correctly define the characteristics of the construction materials. Knowledge of the building is generally gained through direct in situ observation. This approach has certain limitations, including the need to reach the buildings, subjectivity in interpretation, and limitations in accessibility regarding viewpoint, lighting conditions, etc. This work proposes applying modern 3D surveying techniques (Di Stefano et al. 2021) at the early stages of investigation (Tucci et al. 2017) to overcome the limitations mentioned above. In fact, the 3D model can be considered as the digital representative of the real building and it can be shared offline or online to be observed simultaneously by several experts, allowing for a comparison of opinions and training activities for less experienced staff; the information provided by the intensity of the reflected signal allows details, textures, and materials to be recorded even in low light conditions; furthermore, the 3D data acquired can be used to obtain the metric information necessary for more detailed structural analysis and simulations (Sammartano et al. 2023) (Todisco et al. 2024).
This study is part of a broader research project aimed at supporting seismic vulnerability assessment of historical religious buildings. However, in this specific paper, seismic vulnerability aspects are addressed only as an application context, while they have been addressed in depth in (Colapietro et al. in press). The parish churches of Lunigiana, a historic Italian region with a significant seismic past and a rich architectural tradition, are considered.

1.1 Case study

The historical buildings here considered are those already mentioned in the papal bull of Pope Eugene III (1148) and belonged to the ancient Diocese of Luni (Figure 1) (Colapietro, 2022), an area nowadays pertaining to the provinces of La Spezia and Massa Carrara.
The current architectural state of these churches results from a stratification of conservation interventions, functional adaptations, and long-term processes of material degradation (BeWeb). In several cases, the impact of recurrent seismic events has necessitated extensive reconstruction campaigns, significantly compromising the readability of the original structural and architectural configurations.

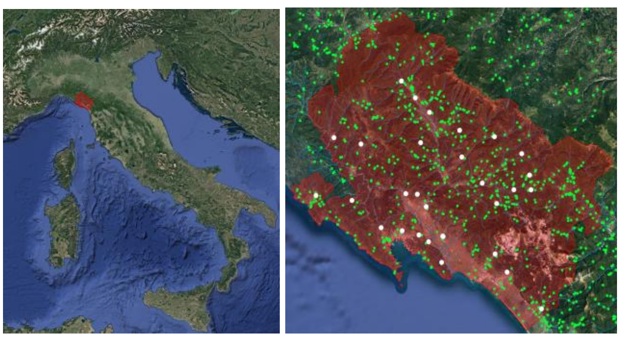


Figure 1. Churches of the Diocese of Luni (in white) in Lunigiana territory (in red); all the religious buildings in the area are indicated (in green)

Of the 35 parish churches belonging to the Diocese of Luni, six are examined in this paper (Figure 2): Church of Santo Stefano (P01), Church of Santa Maria (P04), Church of Sant’Andrea (P05), Church of Trebiano (P08), Church of Vico (P26) e Church of Sorano (P27).

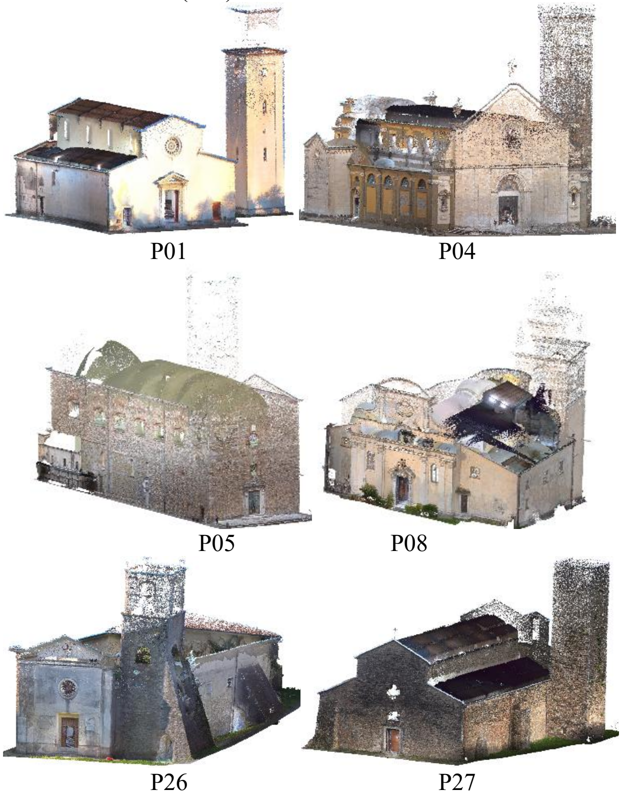


Figure 2. 3D survey of the considered Parish by SLAM-based systems: Church of Santo Stefano (P01), Church of Santa Maria (P04), Church of Sant’Andrea (P05), Church of Trebiano (P08), Church of Vico (P26) e Church of Sorano (P27).

The survey of the churches was carried out using Stonex's portable SLAM X70GO system, equipped with a GNSS-RTK module that allows direct georeferencing of the acquired data (Figure 3). The scans, conducted both inside and outside the buildings, were planned following ring paths, a useful strategy to strengthen the acquisition geometry and reduce drift, a major criticality of SLAM systems.

Figure 3. Stonex X70GO with RTK module during fieldwork.

Each SLAM-based system has specific characteristics that influence its performance, versatility and operating times. The main differences concern the physical configuration of the instrument, the type and number of LiDAR sensors, the presence of cameras, the availability of a RTK module for georeferencing (Table 1).

Device configuration	Handheld
N° LiDAR	1
Points per second	200.000 pts/s
N° of cameras	2
Visual SLAM	yes
Camera resolution	12 MP
RTK GNSS	Integrable
Declared accuracy	6 mm
Processing software	STONEX GOPOST

Table 1. Main specs of X70GO

2. 3D data supporting preliminary seismic vulnerability assessment

Analytical seismic vulnerability assessment requires knowledge of the structure at both geometric and mechanical levels, while preliminary and simplified approaches rely on limited field data collection, typically a complete visual inspection by a skilled specialist, even without any 3D data recording.
In the literature, various approaches exist for assessing seismic vulnerability, ranging from rigorous methods applied to individual buildings to methodologies used for large-scale evaluations (Lagomarsino, Podestà, 2004).
This work considers two expeditious methods for assessing seismic risk vulnerability and analyses how data collected with SLAM-based surveying can support this process. It then extends the analysis to a more generic reading of the structural aspects that characterize the historic buildings considered and describes how 3D models can be processed to produce useful information.

2.1 Collapse mechanism analysis (Level LV1 of Italian regulations)

The Italian legislation (DPCM 2011) provides guidelines for seismic risk prevention in national cultural heritage and criteria for assessing seismic vulnerability in various historical and architectural typologies. Specifically, three levels (LV1, LV2, and LV3) are identified based on the accuracy and depth of the analyses. LV1 summarises the building’s susceptibility to damage based on its construction characteristics and conservation state. It considers the main elements of the building (macroelements) and their associated collapse mechanisms, noting that each macroelement may be affected by different failure modes; the presence of anti-seismic devices and an assessment of vulnerability indicators, in addition to any evidence of damage, are generally evaluated based on direct observation in situ and available documentation. When information is insufficient, a cautious approach is adopted, which, in turn, leads to an overestimation of vulnerability. A better understanding of the building, therefore, optimizes the effectiveness and efficiency of the interventions that can be planned based on these analyses.
Figure 4 exemplify how observing the model allows us to recognize and qualify the elements being evaluated. In this case, the evaluation is done simply by observing the 3D model, assumed as the digital referent of the real building. Considering the façades of various churches, some of the elements whose presence and characteristics contribute to the Level LV1 assessment are highlighted.

(a)

(b)

(c)

Figure 4. Analysis of earthquake-resistant structures and elements in the collapse mechanisms: bonding in Church of Sant'Andrea (a), contrast element in Church of Sorano (b), tie-rod anchor in Church of Santo Stefano (c).

More detailed considerations on this subject were presented at the SAHC 2025 conference (Colapietro et al., in press), where the authors proposed associating the pure i_v index with a "confidence level", defined on the basis of the completeness of the available documentation necessary for the assessment and useful for highlighting the situations of risk overestimation mentioned above; in Figure 5 is the graph of the i_v index for all the churches considered in the project, calculated as in (DPCM 2011) and associated with the confidence level.
Observing the 3D model of buildings provides an adequate understanding of current structural conditions, particularly by identifying pushing elements, such as vaults and arches, the type and quality of materials used, their state of preservation, and the effectiveness of connections between the different structural components. The availability of information on the building's geometric dimensions also allows for estimating the actual slenderness of the walls, a relevant parameter for evaluation, thereby improving their overall reliability.
The calculation of the vulnerability index i_v, in any case, has a subjectivity component, and even with respect to this aspect, having a 3D model is advantageous, as it can be easily shared, allowing different technicians to make the evaluation or at least exchange opinions on certain aspects.
Obviously, some factors of uncertainty remain, mainly due to the presence of plaster or the limited accessibility of some parts of the building: the actual clogging of the walls, the uniformity of the masonry, the presence of adequate architraves and curbs, the specific connections with the roof (beams and chains), the concentrated loads transmitted by the roof and the identification of the elements of vulnerability of the bell cell can remain difficult to interpret even in the face of a detailed survey and require the integration of direct investigations with the analysis of archival documentation.

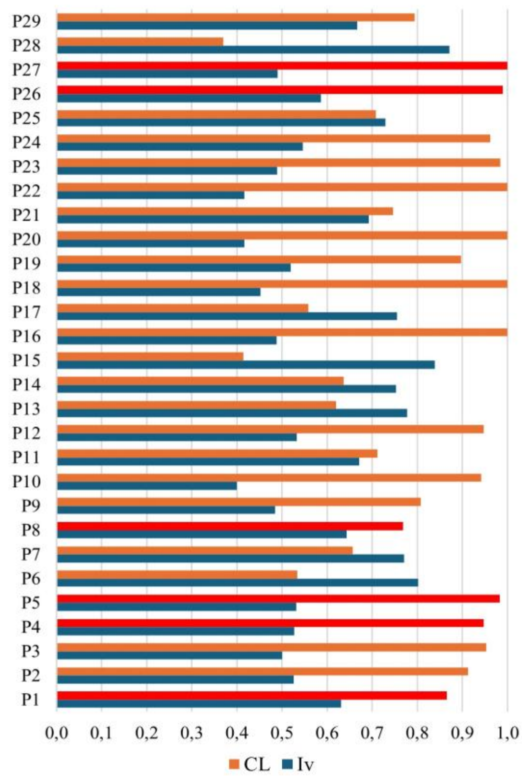


Figure 5. Vulnerability index i_v (blue bars), and confidence level (orange bars) based on the available documentation for all the churches considered in the project; the confidence level (CL) of the churches analysed in this paper is highlighted in red.

2.2 Numerical Indices Based on Structural Dimensions

The three vulnerability indices proposed by (Lourenço et al. 2013) are based on overall dimensions and load data. They account for the in-plane behaviour of the entire structure, in each of the main directions of the church's plans. Compared to the subjective evaluations of the previous method, it produces more objective and comparable results even if there are subjective parameters that can influence the result, in particular the evaluation of the quality and type of walls and the estimation of the weight of the vaulted roof, if the thickness and material are not known.

Geometrical information can obviously be derived from the 3D model with considerable accuracy. In fact, it is worth noting that if only approximate metric data are available, as was the case in this study for some buildings (Figure 6), the indices may vary, particularly when the values are close to the safeguard limit threshold. Under such conditions, a reliable precautionary approach cannot be adopted following this method for vulnerability assessment. Despite the evident differences between the two surveys in Figure 6, the value obtained from the current survey differs only minimally from that obtained from the approximate survey, obtaining, for example, a y_{3x} index ranging from 1.60 for the SLAM survey to 1.58 for the direct survey.

Even if small variations in the index can lead to exceeding the threshold values, it should be pointed out that the advantage offered by the SLAM survey in this context is substantially related to its "convenience" of exploration and speed of execution, which allows for the recording in a short time of a significant number of buildings distributed over a large territory with infrastructures that are not always optimal, as in the case of the parish churches of Lunigiana.

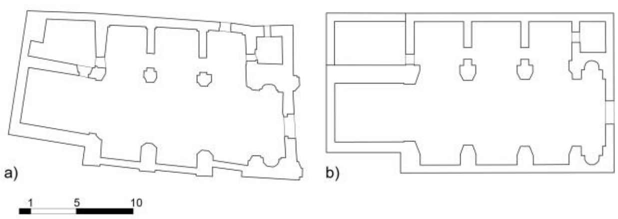


Figure 6. Comparison between plan drawings obtained from (a) X70GO system survey and (b) rapid direct survey archive provided by Massa Carrara-Pontremoli diocese.

3. Analysis of the structure and its deformations

Historical transformations, such as the addition of structural elements or the replacement of original materials, have significantly affected churches' seismic response. These interventions often introduced structural discontinuities and altered the original load paths, thereby increasing the building's vulnerability. An accurate assessment of the seismic vulnerability of such historic structures requires detailed information on their current structural condition, historical evolution, and any past seismic events that have affected them.

In the field of architectural and structural investigations, SLAM systems represent a topic of growing interest for the scientific community (Tucci et al. 2018) (Chiabrando et al. 2018). Numerous studies have analysed the accuracy, reliability and potential of these tools (Malinverni et al. 2018) (Sammartano et al. 2018) (Gharineiat et al. 2024) in the documentation of historical built heritage (Barba et al. 2021). Data type and quality directly influence structural reading (Ioannides et al. 2023). In this broader context, this paper aims to assess the effectiveness and efficiency of SLAM-based surveys, proceeding from the general, such as the quantification of the main geometries of the building, and gradually moving on to more detailed analyses, from the assessment of deformations to the crack pattern.

3.1 Definition of structural elements

Reading volumes, structures, and spaces is the first step in entering the study of historical buildings. Plans and sections can be easily derived from the point cloud: some studies have proposed automatic methods (Chiabrando et al. 2016), although in the field of historic buildings specific skills are generally necessary for the correct and exhaustive representation of buildings (Quattrini et al. 2016).

Relevant aspects of SLAM-based surveying in this regard are the accuracy of the 3D model and its completeness. Both aspects were investigated in (Bonora and Colapietro, 2026); here, a sample analysis is reported for one of the churches surveyed using different SLAM systems (Figure 7). Despite similar acquisition strategies (closed and redundant paths) and georeferencing approaches (target-based), one of the models shows a non-negligible residual drift in the apse area. Along the lateral wall, the estimation of the masonry thickness exhibits centimetric variability, whereas in the case of the apse the three instruments are less consistent in terms of section measurement, and one of the profiles is clearly shifted.

Figure 7. Church of Santo Stefano: overlay of the floor plans from the X70GO (magenta), VLX 3 (blue), and Lixel L2 PRO (green) datasets; zoomed view of the overlay of (a) the section at the apse and (b) the right lateral wall section.

3.2 Deformation analysis

Different types of action can cause deformations in various structural elements. Recognizing these deformations, characterizing their behaviour, and quantifying their extent can suggest their causes and reveal the structure's history, also allowing it to be monitored over time. The structural assessment

of actual or potential damage can therefore be supported by interpreting these phenomena.
The Church of Vico's cross section in Figure 8 compares the hypothesis of an undeformed profile with the surveyed one. In this case, the geometric evidence is corroborated by documentary sources (BeWeb), which report a foundation settlement; this event presumably also led to the construction of the substantial external reinforcement of the apse in 1967.

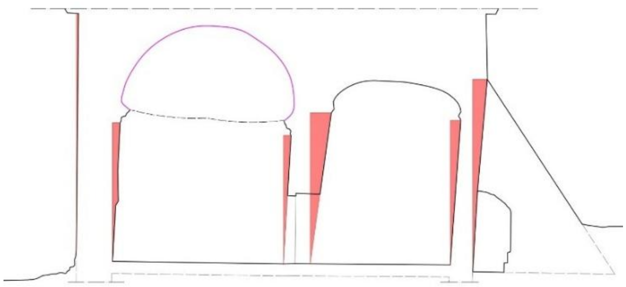


Figure 8. Church of Vico (P32): section highlighting significant structural damage

While cross-sections characterize a local condition, a continuous description of the deformations is often appropriate (Sacco et al. 2024). An effective tool for quantifying and visualizing deformations is the deviations analysis between the point model and a reference geometry, which, in the simplest cases, consists of a plane and, in more complex cases, of manual or parametric models that hypothesize the building original structural configuration. The following are two examples that highlight how the 3D model can contribute to structural diagnostics and the assessment of the state of conservation.

3.2.1 Sorano Church, external wall: The vertical section of the external wall highlights clear out-of-plumb conditions on both faces, which are not constant along the longitudinal development of the walls (Figure 9). Figure 10 illustrates, using a colour scale in which distances increase from blue to red, the deviations with respect to two vertical planes coincident with the walls at the top: the external facing shows limited deviations, on the order of a few centimetres, indicating an overall regular surface with no significant deformations. By contrast, the internal wall exhibits a clear batter (0.40 cm), which can be interpreted as a constructional device aimed at increasing structural stability.

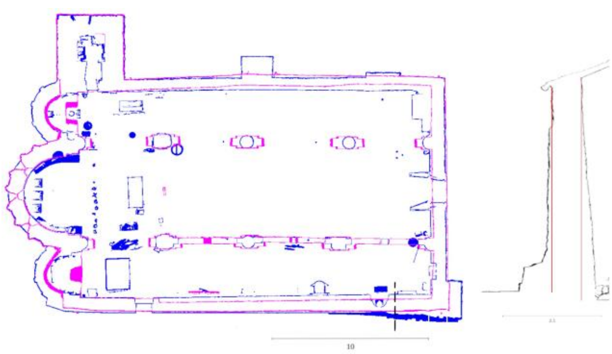


Figure 9. Church of Sorano: Overlay of the floor plans at elevations +1.00 (blue) and +5.00 (magenta).

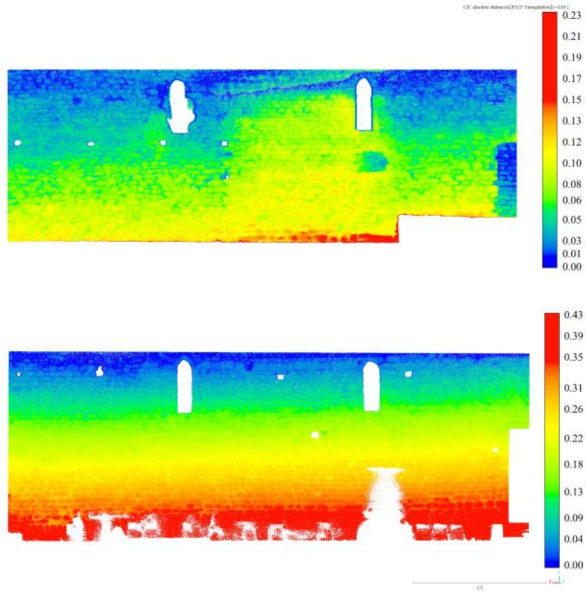


Figure 10. Church of Sorano: analysis of the verticality of the right wall (up) outer and (down) inner façade.

3.2.2 Sorano Church façade: The analysis of the façade of the Church of Sorano (Figure 11) revealed the presence of deformations and bulging distributed across several areas. Maximum deviations reach approximately 20 cm and exhibit a behaviour characterised by a relatively stable base, bulging concentrated in the central zones, and a slight out-of-plumb condition in the upper portion. Historical seismic activity and undocumented elevation interventions may have altered the original load distribution, contributing to the façade deformation.

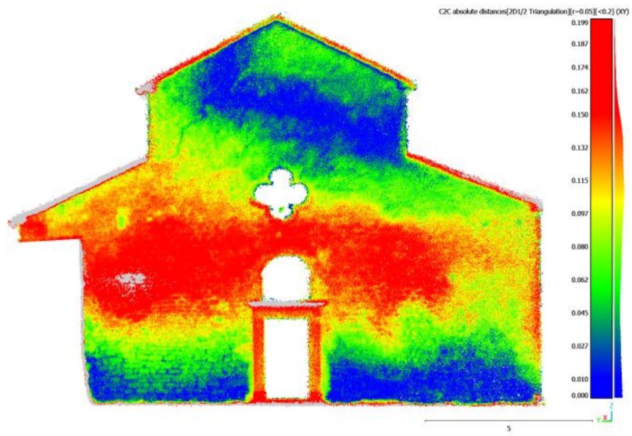


Figure 11. Analysis of the planarity of the Church of Sorano façade.

3.3 Cracks framework – density and noise

The study of crack pattern is important for assessing the damage in buildings and several studies are attempting to automate the recognition process by using photogrammetric or laser scanner surveys (Guerra and Galantucci, 2020); mapping and classification allow to evaluate their diffusion and extent. Compared to a scale laser scanner survey of the building, these elements are, except in some cases of macroscopic lesions, dimensionally critical with respect to the measurement capabilities of TLS (Wang et al. 2024). In the case of SLAM-based systems the conditions are obviously even less favourable. In (Bonora and Colapietro, 2026) we analysed the georeferencing accuracy and the overall 3D models accuracy; here, instead, we neglect global effects such as absolute positioning errors or SLAM-related drift effects to specifically assess the local detectability of crack-related features within a limited portion of the model: global effects primarily impact the global correctness of the model but do not significantly influence local geometric contrasts, which are instead governed by measurement noise, point density, and observation geometry.

3.3.1 Noise: A test was conducted to quantify noise in data acquired by the X70GO system, with the aim of providing an operational characterization of the measurement noise under typical acquisition conditions rather than an absolute sensor calibration. A planar reference surface (about 1 m x 1 m) was then extracted directly from the SLAM survey of the Church of Sorano, and used as a geometric reference (Figure 12). The validity of this reference was assessed by comparing planes estimated from different range-limited subsets of the data, yielding angular differences between plane normals on the order of 0.01° and offsets below 0.3 mm, which are negligible with respect to the observed residual dispersion. Based on this validated reference, the noise was estimated from the orthogonal residuals to the plane and characterized using RMS; given the close agreement between RMS and robust MAD estimates across all tests, RMS values are reported as representative noise metrics (Table 2).

Figure 12. Church of Sorano: the panel used for noise analysis.

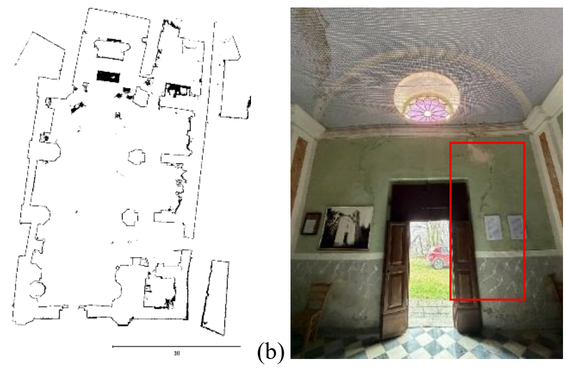
The estimated noise level on two independent dataset, acquired along a different trajectory but covering the same surface, is approximately 2.5 mm for close-range acquisition (within 5 m), increases to about 2.6 mm for typical indoor acquisition (within 10 m), and reaches approximately 2.8 mm when no range filtering is applied, reflecting a mixed-range operational scenario.
Since the reference plane is derived from real survey data rather than from a controlled calibration target, residual effects related to surface non-ideal planarity or SLAM-related low-frequency distortions cannot be entirely excluded, although they were shown to be negligible with respect to the measured noise levels. Consequently, the reported values should be interpreted as practical indicators of expected measurement uncertainty for similar survey configurations, rather than as intrinsic, range-normalized sensor noise parameters.

Dataset	Range condition	Total points	Inliers	Inlier rate	RMS [mm]
P03	≤ 5 m	5,675	5,675	100.00%	2.5
P03	≤ 10 m	7,776	7,769	99.91%	2.6
P03	All ranges	9,775	9,754	99.79%	2.8
P01	≤ 5 m	3,281	3,274	99.79%	2.5
P01	≤ 10 m	4,974	4,960	99.72%	2.6
P01	All ranges	5,629	5,593	99.36%	2.7

Table 2. RMS values computed from orthogonal residuals of inlier points with respect to the fitting plane (two acquisition paths are considered).

3.3.2 Point density: The proprietary software released with X70GO, GOPOST, provides an option for producing, after SLAM optimization, a "densified" point cloud. Even without a more detailed description supplied by the producer, one can infer that it is an oversampling method that depends on the original cloud's resolution and produces a model three times denser, exploiting the camera's image resolution.

3.3.3 Effect of noise and density on cracks recognition: Several researchers have attempted to map cracks based on TLS surveys (Wang et al. 2024), demonstrating that small defects are near the practical resolution limit of that system (Suchocki and J. Katzer 2018). Some tests carried out on the buildings considered in this study highlight that, even when crack apertures fall below the geometric noise level, their presence may still be inferred from point dropout patterns, i.e., localized reductions in point density caused by the inability of the laser beam to generate returns within narrow or concave discontinuities, as shown on TLS data by (Laefer et al. 2010). This possibility should clearly be referred to as "detection" rather than "measurement" of the crack pattern.
Given an estimated measurement noise of approximately 2.5–3 mm (1σ) under the considered operational conditions, the reliable geometric detectability of crack-related features is expected only for amplitudes significantly larger than the noise level, typically beyond 3σ (≈1 cm) in real-world data. Features with amplitudes on the order of 2σ (≈5–6 mm) lie at the detection limit and may be identified only under favourable sampling and incidence conditions, often requiring complementary cues (e.g., intensity/RGB contrasts or point dropout patterns) rather than metric depth measurements. Figure 13 shows a vertical fracture next to the entrance to the Church of Vico, with a maximum width of approximately 4 cm, making it clearly visible in the point cloud, particularly in the densified version. Considering the different buildings surveyed - i.e., with non-homogeneous materials and construction characteristics and slightly varying survey conditions - we can conclude that fractures with centimetre-scale widths are recognizable in the point cloud model.



(a) (b)

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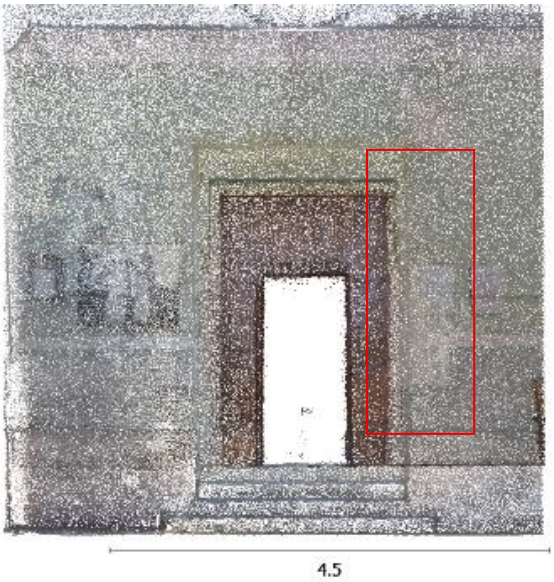

(c)

(d)

Figure 13. Church of Vico: (a) plan, (b) counter-façade (photo). Cracks on the counter-façade: point cloud (c) "standard" and (d) "densified".

4. Conclusions

The paper considers the use of SLAM-based mobile mapping systems for the geometric documentation of historical parish churches, with the aim of assessing their effectiveness and efficiency in supporting different levels of structural and seismic vulnerability analysis. The case study conducted on six churches in the Lunigiana area demonstrates that these systems provide a rapid and operationally flexible solution; their speed of acquisition and ease of deployment make them particularly suitable for large-scale survey campaigns and for the early stages of knowledge acquisition.

The generated 3D models proved to be especially effective in supporting expeditious vulnerability assessment methods, such as LV1 analyses based on collapse mechanisms and simplified vulnerability indices. The possibility to inspect macroelements, identify structural connections, and extract geometric parameters from the models contributes to reducing uncertainties associated with limited documentation and subjective in situ observations. Moreover, the digital nature of the models facilitates data sharing among specialists, improving transparency and consistency in the evaluation process. At a more advanced level, SLAM-derived data also enable the identification and interpretation of significant structural deformations, such as out-of-plumb walls and façade bulging, with an accuracy adequate for building-scale diagnostic purposes.

Conversely, limitations emerge when addressing fine-scale damage phenomena. The experimental analysis of noise and point density confirms that reliable geometric detection is generally restricted to centimetre-scale crack openings, while smaller discontinuities fall near the practical detection threshold. As a result, SLAM-based surveys should be regarded as complementary to higher-resolution techniques when detailed crack measurement is required. Overall, the study confirms that SLAM systems offer a favourable balance between efficiency and effectiveness for preliminary and intermediate structural analyses of historical churches, provided that appropriate acquisition strategies, control measures, and ex post quality assessments are adopted.

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