Sensor integration for the documentation and planned maintenance of Cultural Heritage

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Abstract

The sustainable preservation of cultural heritage, encompassing both tangible assets like monuments and intangible expressions such as traditions, necessitates proactive, evidence-based conservation strategies. This paper underscores the importance of rigorous, continuously updated documentation as the cornerstone of planned maintenance practices, an approach that ensures early detection of vulnerabilities, minimizes invasive interventions, and promotes the longevity and integrity of heritage assets. Within this context, UNESCO's World Heritage framework emphasizes the need for detailed documentation and systematic monitoring, particularly for complex sites like Italy's Sacri Monti, a group of devotional complexes recognized for their integration of landscape, art, and architecture. Focusing on the Sacro Monte di Crea in Piedmont, this study details a case-specific strategy for documenting Chapel XVI, which faces critical conservation issues such as biological growth, salt efflorescence, and material degradation. A multimodal geomatics survey was conducted using terrestrial laser scanning, mobile mapping systems, drone-based photogrammetry, and smartphone LiDAR, enabling the creation of a comprehensive, high-resolution 3D dataset. These datasets were processed, aligned, and fused to produce an accurate and scalable digital representation of the site. This robust foundation supports not only traditional maintenance workflows but also emerging applications of artificial intelligence for 3D reconstruction and interpretation. The integration of such technologies marks a decisive step forward in enhancing both the documentation process and long-term conservation planning for vulnerable cultural heritage sites.

1. Introduction

1.1 The Role of Documentation in the Planned Maintenance of Cultural Heritage

Cultural heritage assets, including both tangible elements like monuments, buildings, and artifacts, and intangible expressions such as traditions, rituals, and knowledge, represent the collective memory and identity of societies, since they serve as a crucial, irreplaceable link between the past, the present, and future generations. The preservation of these invaluable assets requires far more than reactive emergency interventions often prompted by sudden damage or advanced decay. In fact, a proactive and strategic approach to planning is needed, deeply grounded in rigorous, multi-faceted documentation (Van Balen, 2017). Detailed, accurate, and systematically updated documentation is the basis of modern conservation, which allows for a comprehensive assessment of an asset's current physical condition, the precise identification of existing and potential vulnerabilities like structural weaknesses, material degradation, environmental threats, and the formulation of targeted maintenance and conservation strategies. Crucially, these strategies can then be based on verifiable, empirical evidence rather than subjective assumptions, aesthetic preferences alone, or incomplete information, leading to more effective and responsible stewardship. Planned maintenance, standing in stark contrast to reactive or corrective maintenance, is a cornerstone of this evidence-based approach, since it involves the scheduled and systematic inspection and execution of minor, preventative repairs on built heritage (Zerbinatti et al., 2021). This proactive cycle is informed directly by continuous documentation and condition monitoring, tracking even subtle changes over time. Such an approach significantly enhances the longevity and integrity of historical structures, reduces the likelihood of extensive and costly future repairs, and aligns seamlessly with the principles of sustainability and minimal intervention that underpin modern conservation ethics. By addressing minor issues before they escalate, planned maintenance preserves more original fabric and minimises the overall impact on the heritage asset (Torres-Gonzalez et al.,2021).

1.2 UNESCO's World Heritage framework

Within this global conservation context, UNESCO's World Heritage framework plays a pivotal and influential role. The inscription of a property on the World Heritage List signifies not only its Outstanding Universal Value and international recognition but also imposes a profound commitment by the State Party to ensure its safeguarding and preservation for future generations (UNESCO, 2024). A key instrument in fulfilling this commitment is the development and implementation of a comprehensive management plan for each site, incorporating robust mechanisms for continuous monitoring of the state of conservation, thorough risk assessment (including disaster risk preparedness), and clearly defined maintenance protocols. Central to the efficacy of all these mechanisms is the unwavering need for reliable, accessible, and up-to-date documentation, which serves a dual purpose: as an invaluable historical record charting the life and changes of the asset, and as an essential technical reference guiding current and future interventions, ensuring consistency and informed decision-making. In a nation like Italy, which as of 2025 hosts 60 sites, the highest number of UNESCO World Heritage Sites globally, the systematic implementation of such best practices is especially pressing and complex. Many of the nation's invaluable cultural assets are situated in remote or geographically challenging areas, are under continuous environmental stress from factors like pollution, climate change, and seismic activity, or are deeply integrated into

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Figure 1. The Sacred Mountain complex in Piedmont and Lombardy Region in Northern Italy – Landsat Imagery.

the living fabric of historic towns and communities. These conditions make planned maintenance and regular monitoring a particularly challenging yet necessary endeavour to ensure their long-term survival and appreciation. In this context of complexity, integrating diverse data sources and utilizing low-cost sensor technologies can significantly aid in this effort, providing crucial insights for informed decision-making and proactive conservation strategies.

2. Case Study

2.1 The Sacred Mountains (Sacri Monti) WHS

Among the most emblematic and spiritually resonant examples of religious and cultural heritage in Italy are the Sacri Monti (Sacred Mountains) of Piedmont and Lombardy (Figure 1). These nine distinct devotional complexes were collectively inscribed on the UNESCO World Heritage List in 2003, recognized for their unique synthesis of art, architecture, and landscape, and their profound spiritual and cultural significance (Zanzi,2005). Developed predominantly between the late 15th, 16th, and 17th centuries, the Sacri Monti emerged as a powerful expression of the Counter-Reformation. This period in Catholic history emphasized the need for accessible spiritual experiences and effective religious instruction (catechism) for the laity, often through vivid visual storytelling that could evoke deep emotional and devotional responses. Each Sacro Monte is conceived as a pilgrimage route, typically ascending a hillside or mountain, comprising a series of chapels and other religious edifices. These structures are strategically distributed along a natural, landscaped path, and within each chapel, biblical scenes (primarily from the Life of Christ, the Virgin Mary, or Saints) are recreated using life-sized, often dramatically posed polychrome statues and illusionistic frescoes, creating immersive and theatrical environments.

2.2 The Case Study of Sacro Monte di Crea

The Sacro Monte di Crea, situated on one of the highest hills of the Monferrato region in the province of Alessandria (Piedmont), stands as one of the most ancient and significant among the nine recognized complexes. The site’s sacred origins are traced back to a Marian sanctuary, traditionally attributed by local legend to the initiative of Saint Eusebius of Vercelli in the 4th century, who is said to have installed a statue of the Virgin Mary. This early Marian cult laid the foundation for its later expansion into a fully articulated Sacro Monte, a process that began in earnest in 1589. Today, the complex (Figure 2) includes 23 chapels depicting the

Figure 2. High definition Orthomosaic of The Sacred Mountain of Crea complex generated via DJI Mavic 3M and processed via Agisoft Metashape Professional software.
Circled in red is Chapel XVI

Mysteries of the Rosary, a prominent sanctuary (the Basilica of the Assumption of the Virgin Mary), and various hermitages, all integrated within a designated natural park that offers panoramic views overlooking the surrounding countryside.

Artistically, the chapels of Crea are a treasure trove, showcasing the work of prominent regional artists and skilled craftsmen of the period, who employed materials like terracotta for the sculptures, valued for its malleability and capacity for expressive detail, and vibrant frescoes to extend the narrative scenes and create illusionistic backdrops. These artistic elements combine to produce immersive, emotionally charged dioramas that narrate episodes from the life of the Virgin Mary and Christ, designed to inspire piety and reflection in pilgrims (Figure 3). Devotionally, Sacro Monte di Crea remains an important pilgrimage destination, particularly for Marian feasts, embedding it deeply within the spiritual life and cultural identity of the local and regional communities. However, despite its historical and artistic importance, the Sacro Monte di Crea presents a multitude of complex conservation challenges that threaten its long-term integrity. The chapels, by their very design and location, are exposed to the relentless effects of natural weathering: freeze-thaw cycles, solar radiation, wind-driven rain, and humidity fluctuations. Vegetation encroachment, including invasive plant species and tree roots, can cause physical damage to structures and alter moisture regimes. Biological growth, such as algae, lichens, mosses, and molds, proliferates on stone, plaster, and painted surfaces, causing aesthetic disfigurement and material deterioration. Furthermore, structural settlement due to the inherent instability of the terrain on which some chapels are built poses an ongoing risk.

Figure 3. Example of statuary complex narrating the lives of Virgin Mary and Christ - The Last Dinner

Figure 4. Chapel XVI, external view and detail of interior statues

2.3 Chapel XVI and its degradation processes

Chapel XVI hosts plaster statues and frescos depicting the Ascent of Christ to the Calvary Hill (Figure 4). It was built at the end of 19th century, and since the second half of the last century a series of restoration interventions have been carried out with the contribution of the Piedmont Region. The most recent ones date back to around 2000 dealing with the roofs and the restoration of the window frames. It has also been subjected to recent restoration interventions, especially concerning the exteriors. Despite that, the degradation this small chapel undergoes is still of significant extent (Figure 5) and is characterized by various components, such as growth mainly of mosses and lichens, leading to the creation of a humid chemical microenvironment and to the physical and chemical disintegration of the surfaces they affect; capillary action, linked to a series of contributing causes related to the forces of adhesion between the fluid and the material involved; effects of salt efflorescence, specifically salt crusts on the lower internal surface of the walls, generated by the evaporative processes of interstitial water within the wall structures. The inherent fragility of the sculptural ensembles (terracotta is susceptible to cracking and breakage) and the delicate nature of the frescoes (vulnerable to moisture, salts, and detachment) mean that frequent, invasive physical inspections are highly undesirable as they can inadvertently cause further stress or damage. This context significantly amplifies the need for non-destructive, remote, and efficient documentation techniques that can provide comprehensive data to inform a meticulously planned maintenance regime, allowing for early detection of problems and targeted interventions.

Figure 5. Detail on Chapel XVI's degradation processes

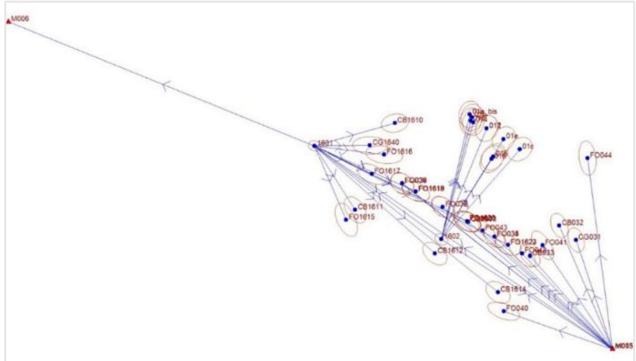

Figure 6. Network Adjustment around Chapel XVI via MicroSurvey STAR*NET software

3. Instruments and Techniques for an Integrated Survey

To effectively address these pressing conservation needs while ensuring methodological rigor, cost-effectiveness, and operational efficiency, a comprehensive and integrated geomatics strategy was adopted for the documentation of Sacro Monte di Crea. The selection of instruments was carefully considered to combine the strengths of high-accuracy, high-resolution laser scanning (Fassi et al., 2013) with the versatility, speed, and accessibility of consumer-grade and advanced mobile mapping technologies (Murtiyoso and Grussenmeyer, 2021). Each instrument offers unique advantages and is best suited for specific aspects of the documentation process, depending on the scale and nature of the object of study, its accessibility, the required level of detail and accuracy, and the intended downstream use of the acquired data.

3.1 Topographic Network

The first step of an integrated multimodal and multi-scalar acquisition is the definition of a topographic network around the object to be surveyed (Figure 6), by using GNSS receivers on the network vertexes, RTK receivers on GCPs (Ground Control Points) and total stations to measure the coordinates of detail points, such as those on the facade and inside of the chapel. Thanks to this crucial step, the point clouds generated with the different techniques can be georeferenced with high accuracy.

3.2 Terrestrial Laser Scanner

Terrestrial Laser Scanning (TLS), like Leica RTC360, provides millimetric accuracy and boasts rapid data acquisition rates up to 2 million points per second. It also features integrated HDR (High Dynamic Range) cameras for capturing imagery, allowing for the automatic colorization of the resulting point clouds, which greatly aids in interpretation. TLS is ideal for capturing highly detailed and accurate 3D geometries of architectural structures, sculptural elements, and intricate details both in interiors and exteriors (Figure 7). This level of precision is critical for tasks such as crack detection and mapping, deformation analysis over time, and creating precise baseline data for monitoring structural health (Kaartinen et al.,2022). However, TLS systems require multiple setups to cover complex areas, which, depending on the geometry of the building, may result in time-consuming activities and in unmapped portions in difficult conditions or tight spaces.

Figure 7. A portion of Leica RTC360 TLS Point Cloud

3.3 Mobile Mapping System

Mobile Mapping System (MMS), on the other hand, are based on SLAM (Simultaneous Localization and Mapping) algorithms, which enables the device to build a map of its surroundings while simultaneously tracking its own position within that map, often using a combination of LiDAR sensors, cameras, and Inertial Measurement Units (IMUs). Handheld scanners like the Stonex X70GO excel in capturing data in narrow, cluttered, and complex environments, like tight spaces around the chapels (Figure 8) where static scanning would be impractical or excessively time-consuming (Elhashash et al., 2022). While the accuracy of MMS is of centimetre-level, it provides the data in real-time and is especially suitable for generating quick overviews of extensive areas, or for repeated monitoring campaigns where speed is prioritized over utmost accuracy.

3.4 Uncrewed Aerial System

UAS (Uncrewed Aerial System) Photogrammetry, with compact systems like the DJI Mini 3 Pro. They consist of drones equipped with high-resolution digital cameras, such as the 48MP camera on the DJI Mini 3 Pro, enable the acquisition of numerous overlapping aerial images, which are then processed using Structure-from-Motion (SfM) photogrammetric techniques to generate dense 3D point clouds, textured meshes, and orthophotos. UAS photogrammetry is particularly effective for documenting inaccessible or difficult-to-reach areas like roofings or upper portions of the chapel (Figure 9), as well as for mapping larger areas of the surrounding landscape or park. The lightweight nature and economic impact of drones like the Mini 3 Pro also minimise logistical challenges and operational costs (Ulvi, 2021).

3.5 Short-Range LiDAR and Photogrammetry

Smartphone-Based LiDAR and Photogrammetry (e.g., iPhone 15 Pro + Pix4DCatch app): The increasing integration of LiDAR sensors, though typically with shorter range and lower resolution than dedicated scanners, and sophisticated photogrammetry apps on high-end smartphones represents a significant democratisation of 3D documentation tools (Teppati Losé et al., 2022). While the accuracy and range are quite limited compared to professional-grade instruments (Figure 10), the ubiquitous

Figure 8. Portion of Stonex X70GO Point Cloud

Figure 9. Portion of DJI Mini 3 Pro Point Cloud

Figure 10. iPhone 15 Pro Point Cloud via Pix4DCatch

nature, ease of use, and extreme affordability of smartphones make them a viable option for initial reconnaissance, documenting smaller objects or specific details, empowering local stakeholders or non-experts to contribute to documentation efforts, or for frequent, low-cost routine condition updates. The strategic and combined use of these diverse instruments ensures data redundancy (multiple datasets of the same area using different techniques), versatility (ability to adapt to various scales and complexities), and scalability (efficiently documenting everything from a single sculptural detail to the entire complex). Each tool contributes a unique layer of information to the final comprehensive documentation, resulting in a robust, multi-modal, and multi-scale dataset. This rich dataset is then suitable for a wide array of applications, including detailed conservation planning, creating accurate 3D models for analysis and visualization, developing virtual tours for public dissemination and education, and establishing a baseline for future monitoring.

4. Creating a Coherent Digital Representation

4.1 Data Processing

The acquisition of raw data from multiple geomatics instruments is only the first step, since processing and fusing these heterogeneous datasets (Martino et al., 2023, Tini, M. A. et al., 2023, Blaszczak-Bak, W. et al., 2024) into a coherent and usable digital representation is a critical subsequent phase. This process follows a modular yet ultimately integrated pipeline, where data from each sensor is first treated individually before being combined. Each dataset undergoes an initial pre-processing within different software environment.

Specifically, Terrestrial Laser Scanning (TLS) data are treated in the proprietary software Leica Cyclone Register 360 Plus, in which the seven static scans are aligned and registered together to create a complete point cloud of the chapel. This process is achieved by identifying common points visible in overlapping scan positions and by using cloud-to-cloud alignment algorithms. For both the iPhone and UAS Photogrammetry data, processing occurs in SfM software, in this case Agisoft Metashape Professional, which for our purposes involves a pipeline composed by image alignment (identifying tie points across multiple images), known coordinates point measuring on the images, camera calibration, generation of the dense point cloud, but which may also include other phases such as mesh generation, texturing, Digital Elevation Model (DEM) and orthophoto definition. Finally, for the SLAM-based system, the proprietary software GOPost has been used. Among the processing steps, trajectory optimisation and loop closure detection are crucial, since the estimated path of the sensor during data acquisition is refined, correcting for drift and improving the overall geometric accuracy of the resulting map or point cloud.

4.1 Data Fusion

Once pre-processed, the individual datasets (TLS, UAV, SLAM and iPhone) are imported into a common environment, the open-source software CloudCompare. The point clouds, which are already aligned thanks to the initial use of GNSS receivers and total stations, are subsampled to manage data within the same spatial extent. Since no single instrument or dataset can provide on its own a complete coverage or uniformly reliable information across the entire site or object of study (Figure 11), data fusion is particularly significant. For instance, while TLS provides high-fidelity geometric detail for building facades and interiors, it struggles to capture roof elements or occluded areas in tight spaces. UAV photogrammetry, on the other hand, excels at capturing these otherwise inaccessible upper portions, but lacks coverage of interiors and may have lower accuracy on vertical surfaces compared to TLS. Finally, SLAM systems and close-range acquisitions can rapidly map complex internal pathways

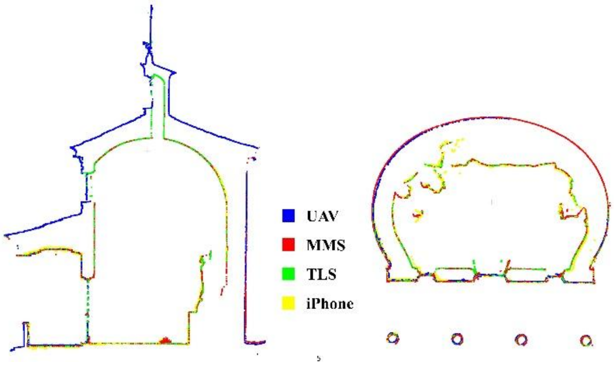

Figure 11. Cross and Planar Sections of the Chapel's point clouds acquired with the different sensors

Figure 12. A portion of the fused dataset

where TLS setups are cumbersome and can fill small gaps or document specific features quickly.

The merged, multi-modal dataset (Figure 12) facilitates comprehensive multi-scale analyses, ranging from the overall geometry and layout of the entire chapel down to the assessment of small-scale material deterioration like spalling stonework or cracking plaster on a specific sculpture. These integrated digital archives form a powerful baseline, supporting ongoing monitoring by allowing for direct comparison with new data acquired over time to detect changes, and enabling more informed and targeted conservation decisions.

4.3 Low-cost Sensors

Among the instruments used, TLS and MMS require a significant amount of financial resources, which may be out of reach for small entities like the ones managing the larger part of our Cultural Heritage. For this specific reason, affordable and compact instruments such as the DJI Mini 3 Pro and an iPhone equipped with the Pix4DCatch application are of great help for making the documentation of CH more accessible. Moreover, the data acquired using these two technologies can easily be managed and processed with open-source Structure from Motion software such as Reality Capture, which require little training.

Figure 13. A portion of the fused low-cost dataset

Additionally, Pix4DCatch offers some cloud-based processing directly from the application, as well as the new feature of 3D Gaussian Splatting, which has not been tried for this contribution since it was not present when surveying our case study. The integration of these two sensors (Figure 13) can easily cover inaccessible areas for TLS and MMS, such as the roofing of the Chapel, which can be captured by UAV imagery, while the interior environment has been acquired via close-range photogrammetry using iPhone 15 Pro. With the same sensor, we could have reconstructed also the details on the back portion of the Chapel which were hidden by vegetation. The point cloud obtained by fusing these two low-cost technologies does not differ much from the one of the TLS, which has been considered as the most accurate geometrically, with more than 50% of the points within the 2 centimetres range and more than 75% of points within 4 centimetres from the ground truth (Figure 14). The result of this comparison is more than enough for some initial documentation of the degradation phases of the building.

5. Artificial Intelligence Techniques for CH Documentation

Beyond the now relatively conventional digital documentation workflows, the rapidly evolving field of artificial intelligence (AI) is poised to significantly revolutionize how cultural heritage is surveyed, analysed, interpreted (La Guardia, M. et al., 2024) , and managed. Among the most promising and actively researched AI developments relevant to this domain, we can find Neural Radiance Fields (NeRF), Gaussian Splatting (GS) and Large Language Models (LLM). NeRF models represent a groundbreaking approach to 3D scene reconstruction and novel view synthesis. They utilize deep neural networks, trained on a sparse set of input images and their corresponding camera poses, to learn a continuous volumetric representation of a scene, which implicitly encodes both the geometry and appearance (color, texture, lighting effects) of the scene. Once trained, a NeRF can synthesize highly photorealistic views from any viewpoint, even those absent in the input dataset. They are particularly adept at capturing fine geometrical details, complex lighting, reflections, and transparencies.

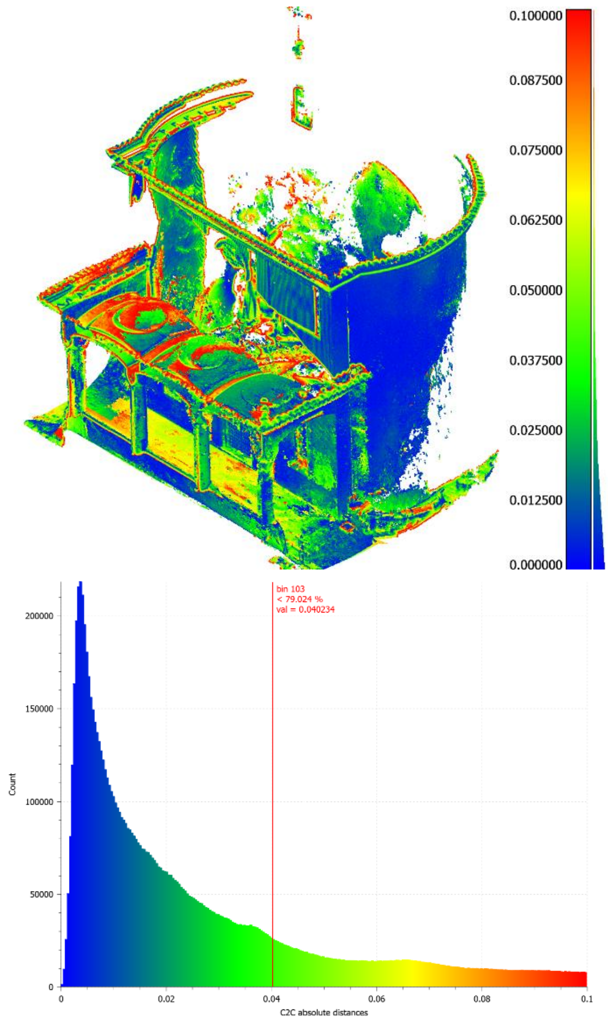

Figure 14. Cloud2Cloud Distance between the TLS point cloud and the low-cost sensors' point cloud (UAV + iPhone)

In cultural heritage applications, NeRFs are ideal for creating immersive and realistic visualizations of sites reconstructing views of damaged or lost artifacts or architectural elements from historical photographs or partial datasets, and for detailed appearance documentation. 3D Gaussian Splatting is a more recent rendering and scene representation technique that has quickly gained traction due to its ability to achieve high-quality, real-time rendering. Instead of representing scenes with traditional polygonal meshes, point clouds, or voxels, Gaussian Splatting models a scene as a collection of 3D Gaussians, characterized by position, orientation, color, and opacity. This representation is highly efficient for rendering, allowing for interactive exploration of complex, richly detailed 3D scenes (Figure 15). In cultural heritage, Gaussian Splatting can be used for large-scale visualization of entire sites or cities, enabling real-time navigation and exploration of highly detailed reconstructions. Finally, LLMs, when combined with computer vision capabilities, can process and interpret both textual and visual information. In the context of cultural heritage, LLMs can support documentation in many ways, such as by Analysing images, 3D models or textual records to automatically generate descriptive tags, keywords, and descriptions of assets and to extract information from digitised historical documents, inscriptions or conservation reports.

Figure 15. 3D Representation based on Gaussian Splatting, generated from UAV and iPhone datasets, processed on Jawset Postshot software.

LLMs can also help users recognise iconographic themes, styles, symbols and elements, potentially linking together broader databases or narratives. Together, these AI tools and others under development (e.g., AI for material analysis, decay prediction, or automated damage detection) offer powerful new avenues to reconstruct heritage that may be physically incomplete, interpret complex historical and artistic information, and interact with heritage sites in more engaging and informative ways. This is especially valuable in contexts where physical access is restricted due to fragility or remoteness, or where historical data is fragmented, incomplete, or difficult to decipher through traditional means.

6. Conclusions

This study, centered on the emblematic case of the Sacro Monte di Crea, underscores the profound transformative potential of integrating advanced geomatics techniques with emerging AI-assisted methodologies. Such an integrated approach is set to revolutionize the entire lifecycle of how we document, analyse, maintain, interpret, and valorize cultural heritage. The experience at Crea illustrates how the strategic combination of high-end, survey-grade technologies like TLS with increasingly accessible and versatile consumer-grade tools like UAS and smartphones can yield exceptionally rich, multi-scalar, and multi-modal datasets, which are not only invaluable for implementing effective planned maintenance strategies and supporting scholarly research but also for creating engaging experiences for public dissemination and education. Moreover, the thoughtful integration of artificial intelligence techniques, such as NeRF, Gaussian Splatting, and LLMs, opens entirely new frontiers, providing unprecedented capabilities for the digital reconstruction of lost or damaged elements, the simulation of historical environments or future risk scenarios, and the development of new, interactive ways to engage diverse audiences with their cultural legacy. This moves beyond static documentation towards dynamic, interpretive, and predictive models of heritage. By fostering inclusivity through more accessible tools, ensuring scalability to address heritage of all types and sizes, and relentlessly pursuing technological innovation, these combined approaches contribute significantly to a more sustainable, resilient, and democratic model of heritage conservation. It is a model where data-driven insights enhance decision-making, where non-invasive methods prioritise the preservation of original fabric, and where both experts and local communities are empowered with the knowledge and tools necessary to safeguard their invaluable cultural legacy for generations to come collaboratively. The future of heritage preservation lies in this synergy between human expertise, precise digital documentation, and intelligent data interpretation.

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