

Integration of 3D Ultrasonic Tomography, Photogrammetry, and Mixed Reality for the Structural Assessment of the Marble Statue "Caino"

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Abstract. Increasingly often, museums and art galleries require non-invasive inspections of marble sculptures on the occasion of transfers or museum loans in order to detect any hidden micro-fractures or internal decay. In this regard, we carried out a complete and non-invasive internal assessment using ultrasonic techniques, to ensure the structural stability of the monumental marble statue "Cain" (Domenico Trentacoste, 1903) from the Galleria d'Arte Moderna (GAM) in Palermo, prior to a planned transfer.

The chosen approach integrates high-resolution digital photogrammetry with 3D ultrasonic tomography (UST). Using a series of scripts developed in MATLAB and Python, we reconstructed an ultrasonic wave velocity model strictly constrained to the geometric shape of the artwork. The data acquisition process involved 370 measurement points, including sources and receivers, and among the possible source-receiver pairs, 520 paths were selected to ensure sufficient coverage of all parts of the statue. The results indicated an average pressure wave velocity of approximately 5000 m/s, and the tomographic inversion confirmed an exceptional compactness of the material without any critical internal defects.

Because raw geophysical data can be difficult for conservators to interpret, we exported the 3D velocity model into Mixed and Augmented Reality (MR/AR) environments. This approach allows users to interactively explore cross-sections of the statue in real-time, offering a highly intuitive method for interpreting non-destructive testing data in conservation planning.

Keywords: Cultural Heritage · 3D Ultrasonic Tomography · Photogrammetry · Mixed Reality · Non-Destructive Testing (NDT) · Tomographic Inversion

1 Introduction

Assessing the structural health of monumental works is an important step in preparing for their relocation. In this regard, non-destructive testing (NDT) represents the established standard for examining the internal condition of statues without causing damage [1–4].

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However, the statue's complex geometry often negatively influences the results of physical models obtained with tomographic methods, which generally require approximate starting models.

Domenico Trentacoste's early twentieth-century masterpiece, "Cain," perfectly illustrates this complexity. Sculpted from fine white statuary marble, the sculpture depicts the biblical figure in a state of profound remorse. His anatomical posture therefore presents protruding volumes and notable morphological variations, causing considerable difficulties in the acquisition of tomographic data and in the subsequent discretization of the model. In view of a planned relocation, the Galleria d'Arte Moderna (GAM) in Palermo requested a comprehensive diagnostic investigation following a preliminary technical inspection conducted in July 2025.

NDT methods struggle to manage particularly complex 3D models, frequently producing distortions in spatial representation and consequent artifacts among the identified anomalies [5, 6]. To minimize these effects, we implemented a diagnostic protocol that combines Structure-from-Motion (SfM) photogrammetry, constrained 3D ultrasonic tomography, and mixed reality (MR) visualization [5, 7, 8]. The resulting model provides a geophysical reconstruction of the elastic wave velocity model, extremely accurate in both form and representation, minimizing artifacts related to geometric distortions. The resulting model represents a very robust tool for assessing the possibility of safely relocating the statue of "Cain," while also providing a powerful tool for visualizing the results for restoration professionals.

2 Related Works

Ultrasound computed tomography (UST) has been a decades-long established technique for assessing the mechanical and physical properties of natural stone [1–3]. The three-dimensional reconstruction of the P-wave velocity field by measuring their propagation times between sources and receivers, placed at appropriate points on the surface, allows for the precise identification of internal defects, ranging from decohesion planes to metallic inclusions [9–12].

However, the highly irregular geometric shape of some sculptures represents a serious obstacle for UST algorithms. Indeed, solving the tomographic inverse problem requires high-precision estimation of the spatial coordinates of the ultrasound sources and receivers [8, 9]. Digital photogrammetry directly addresses this problem, as it allows for the generation of more accurate 3D meshes and, consequently, for the propagation time equations to be constrained to the true physical contours of the artwork, drastically reducing inversion artifacts.

Data interpretation is also evolving. Virtual and mixed reality (VR/MR) platforms are helping to change the way volumetric geophysical data can be represented and viewed. Recent studies in the fields of non-destructive testing (NDT) and geosciences demonstrate that immersive environments recreated by mixed reality offer a much better spatial understanding of 3D information [7, 8, 13]. In the cultural heritage sector, this allows conservators and restorers to intuitively navigate tomographic models [14], significantly improving the decision-making process related to intervention works.

3 Methodology

The methodology discussed in this work is divided into the following phases. First, the measurement points are selected and adhesive markers are used to locate them. Next, a detailed photogrammetric scan is performed to reconstruct a high-detail 3D model of the artwork's surface, including the coordinates of the measurement points. With these spatial constraints, the ultrasonic data is acquired and inverted, using the photogrammetric model as the boundary of the geophysical model. The final phase involves adapting the resulting 3D volume in a VR/MR environment for immersive visualization.

3.1 Photogrammetric Survey

The complex morphology of the "Cain" required careful selection of measurement points to ensure sufficient coverage of the wave paths, which was necessary to obtain an ultrasound velocity model with homogeneous resolution across the entire statue. The digital photogrammetric model of the statue's surface was recreated using RealityScan software [15], which processed 300 high-resolution images, taken from different angles (Fig. 1a), to generate the point cloud (Fig. 1b) together with the textured polygonal mesh (Fig. 1c).

The photogrammetric model obtained and visualized using ParaView [16] was not only for display purposes, but also served a dual purpose in the workflow. The first purpose was to estimate the coordinates of the 370 measurement points (blue dots in Fig. 1c) with extreme precision, ensuring the sensor coordinates coincided with positions on the statue's surface. Furthermore, the generated mesh was used to strictly constrain the subsequent tomographic modeling to the boundary, ensuring that all calculated ray paths remained within the actual volume of the marble, ensuring the physical and geometric consistency of the tomographic inversion process.

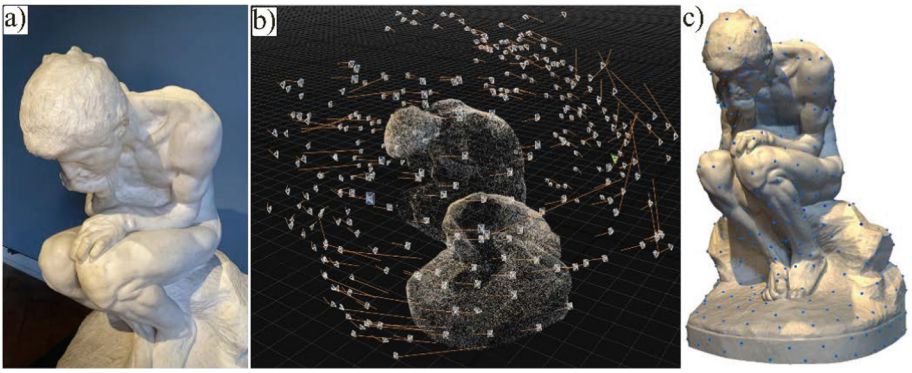


Fig. 1. a) one of the 300 photos of the photogrammetric survey; b) point cloud obtained using RealityScan; c) final textured polygonal mesh of the Caino statue visualized by ParaView. The blue dots indicate the ultrasonic measurement points.

3.2 Ultrasonic Data Acquisition and Tomographic Inversion

3D UST data acquisition was performed using the direct transmission technique. The equipment consisted of a TDAS 16 multichannel system (Boviar S.r.l.), connected to a TSG-55 piezoelectric transmitter and RSG-55 receivers operating at a central frequency of 55 kHz (Fig. 2a). This frequency offers a good compromise between the penetration depth of the ultrasonic pulse and the resolution of the velocity model. The sensors were equipped with conical steel tips specifically designed to ensure localized contact on the curved surface of the marble. However, for optimal acoustic coupling between the sensors and the marble surface, the use of contact gel was necessary to ensure good intensity of the recorded signal. The prohibition of direct contact between the gel and the porous surface of the marble, which could have caused alteration of the latter, was circumvented by applying an ultra-thin, acoustically transparent polyvinyl chloride (PVC) film over the entire surface of the statue (Fig. 2b). The reference markers, necessary to define the acquisition points, were then glued onto the PVC film (Fig. 2c). Finally, ultrasound measurements were taken on the wrapped statue in direct transmission mode (Fig. 2d).

On each acquired ultrasonic signal, the first arrival times of the P waves were manually picked. Any outliers in the dataset were searched for and eliminated by analyzing apparent velocities from the simple ratio between source-receiver distances and the corresponding travel times. A linear regression of travel time versus path length was applied to the filtered dataset to estimate the average apparent velocity (with the straight-ray approximation) to be used as the value for the initial model cells (Fig. 3). The inversion of the estimated travel times was performed using the SIRT (Simultaneous Iterative Reconstruction Technique) algorithm implemented in the GeoTomCG software [17]. This algorithm uses a curvilinear raytracing that takes into account the refractions caused by the velocity variations between the cells into which the model is divided. The solution of the inverse problem starts from an initial model in which each cell of the discretized model is assigned the same average velocity value, obtained from an average of the apparent velocities obtained from the ratio between the travel times and the straight-line distances (homogeneous model and rectilinear raytracing). The model is iteratively updated by the algorithm that tends to minimize the discrepancy between the measured and calculated travel times until a model with minimum stable misfit is obtained. In this research, the optimal model was obtained after seven iterations of the inversion algorithm. A notable feature of this class of inversion methods is that the reconstructed velocity model is generated using a regular Cartesian grid. Although this representation is computationally efficient, it becomes problematic when the actual volume investigated has a very irregular shape, as in most statues. In these cases, the inversion grid necessarily includes regions outside the marble volume, and the corresponding velocity values cannot be interpreted as real material properties. The presence of these external regions can also lead to low-velocity anomalies in the model regions close to the statue's surface, thus complicating structural interpretation if no additional geometric filter is applied. The sequence of steps involved in tomographic inversion is illustrated in the upper section of the flowchart in Fig. 4.



Fig. 2. Phases of ultrasonic data acquisition on the "Caino" statue. a) TDSA acquisition system; b) application of the ultra-thin transparent PVC protective film on the marble surface; c) positioning of reference markers on the wrapped surface to define the measurement points; d) execution of ultrasonic measurements using conical-tip sensors.

3.3 Matlab-Based Data Processing and Geometric Constraint

The most critical phase of the MATLAB routine occurred after the GeoTomCG inversion. The software outputs the reconstructed velocity field as a standard ASCII file, mapping coordinates and velocities across a rigid Cartesian grid. To fix the boundary issues mentioned earlier, we used the high-resolution photogrammetric mesh to physically crop the dataset, stripping away any grid nodes that fell outside the actual marble volume.

Following the SIRT inversion, the resulting ASCII dataset, including spatial coordinates and acoustic velocity values (x, y, z, V), was processed with MATLAB [18], in order to accurately correlate the tomographic data with the boundaries of the statue, obtained from the high-resolution photogrammetric mesh (in OBJ format). Starting from

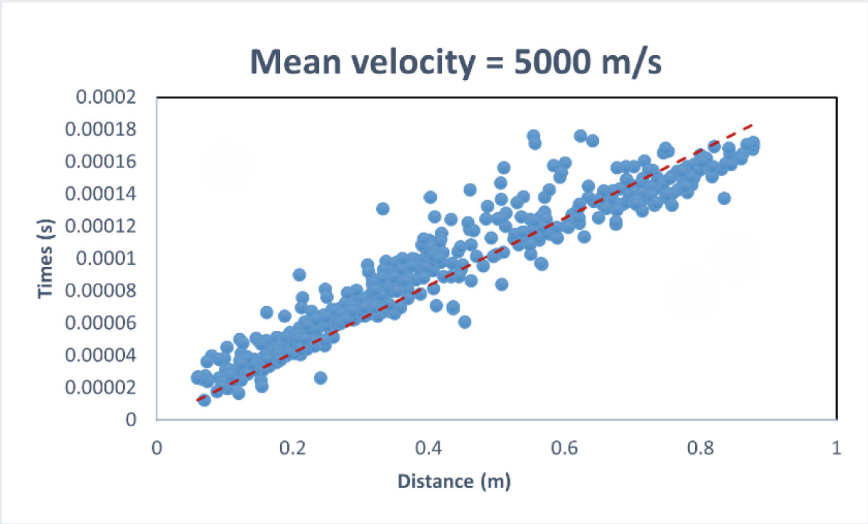


Fig. 3. Travel-time versus source-receiver distance for the filtered first-arrival picks. Linear regression (y = 0.0002x) generate a mean P-wave velocity of 5000 m/s.

the approximate geometry of the inverse model, a regular 3D grid is generated, characterized by a finer spatial resolution (5 mm), whose velocity values are interpolated starting from the velocities of the dataset obtained from the inversion. For the interpolation, the Inverse Distance Weighting (IDW) method was used, through a KD-tree spatial partitioning algorithm, configured with a weighting power equal to 2 and a search radius r of 0.5 m. To strictly limit the tomographic results to the real geometry of the artifact, a geometric constraint is applied using a point-in-mesh test based on a ray-casting algorithm (specifically, the inpolyhedron function). This algorithm evaluates the spatial position of each node in the interpolated grid with respect to the photogrammetric mesh. The voxels of the grid located outside the mesh boundaries are discarded, while the internal voxels are selectively retained. This results in a 3D velocity model completely bounded by the actual geometry of the statue.

The procedure reduced the influence of boundary-related artefacts and improved the physical interpretability of tomographic reconstruction, particularly in geometrically complex areas such as overhangs, curved surfaces, and strongly varying cross-sections. The filtered dataset was then used for three-dimensional rendering together with the external photogrammetric model. The flowchart of the above explained workflow is showed in Fig. 4.

3.4 Augmented and Mixed Reality Representation

To improve the interpretation of the tomographic velocity model, it was integrated into a Mixed Reality (MR) environment. This integration allowed the statue to be visualized at a 1:1 scale, providing the user with a more realistic perception of the spatial distribution of the velocity field within the statue. The 3D velocity model is converted to be usable

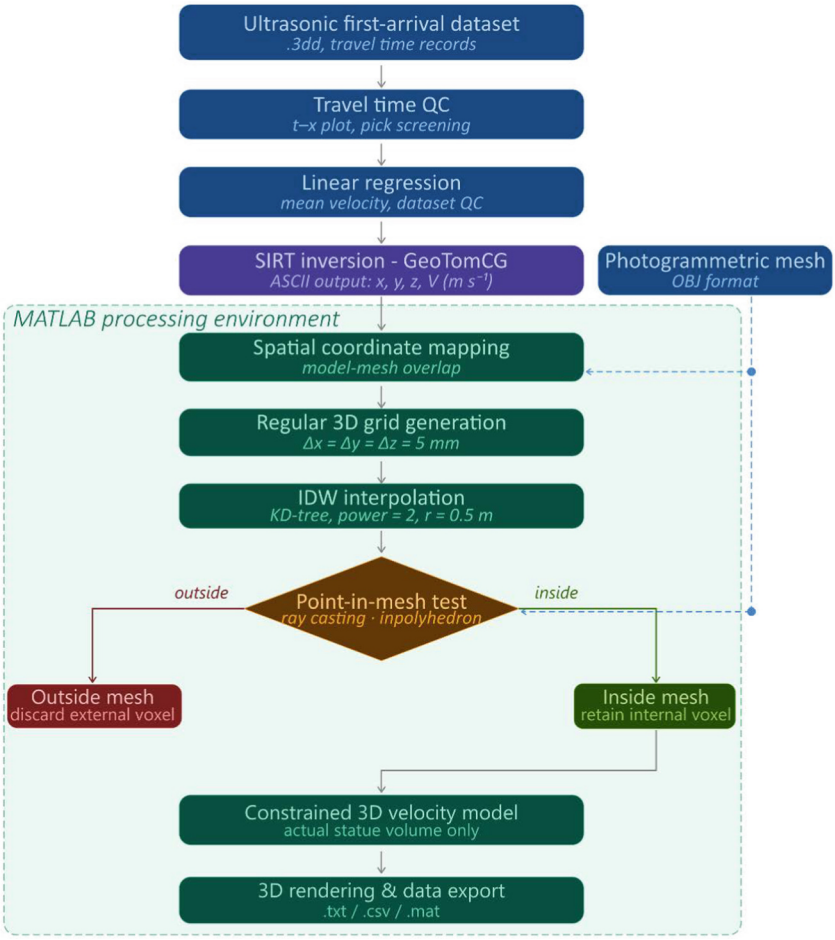


Fig. 4. Algorithmic flowchart of the integrated workflow for geometry-constrained 3D ultrasonic tomography, from first-arrival data preprocessing and SIRT inversion in GeoTomCG to MATLAB-based spatial mapping, IDW interpolation, and point-in-mesh masking of the reconstructed velocity volume using the photogrammetric mesh as geometric constraint.

by modern rendering engines (e.g., Unreal Engine), enabling the user operating in a MR environment to use hand tracking or spatial controllers. This allows for not only static visualizations but also interactive slicing, i.e., the ability to dynamically define, manipulate, and reposition appropriately oriented cross-sections. This can make the analysis of internal velocity anomalies more intuitive and therefore more effective, and consequently, the recognition of any structural inhomogeneities. Ultimately, the use of mixed reality, in addition to being a valid communication and dissemination tool, proves to be an effective support system for diagnosing the state of conservation of the artwork and for subsequent restoration operations.

4 Results and Discussion

The closed triangular mesh produced by the photogrammetric survey rendered the complex anatomical geometry and surface texture of the marble with a precision well above that required both for the georeferencing of the 370 measurement points and for the subsequent refinement of the mesh for the representation of the inverse model in mixed reality.

Preliminary kinematic analysis of the dataset, through the graphical representation of travel times as a function of the corresponding source-receiver distances for all 520 paths, highlighted very few outliers, demonstrating the initial distributional homogeneity of the material. Linear regression of these data showed a global mean P-wave velocity of approximately 5000 m/s, with low variance in the distribution of the data cloud. In the context of statuary marble, this high value indicates a stone matrix characterized by excellent mechanical compactness and a broad structural homogeneity [6].

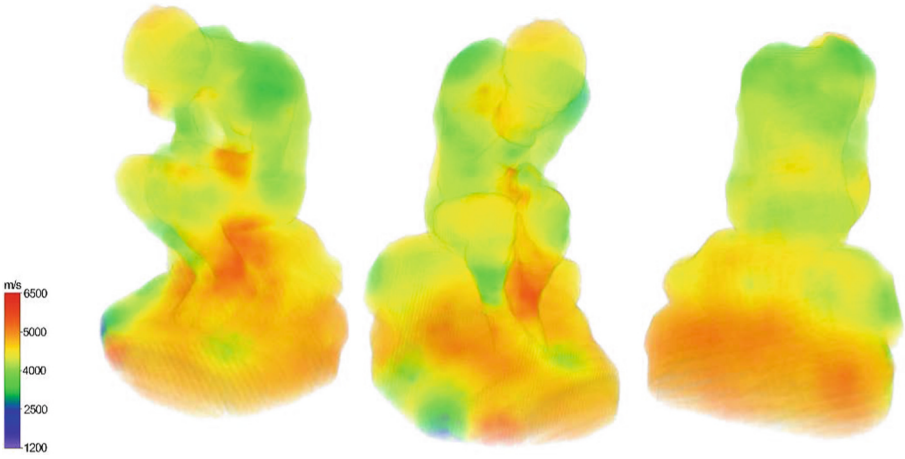


Fig. 5. 3D renderings of the final tomographic velocity model of the Caino statue from three different perspectives. The predominantly green-to-yellow velocity pattern suggests a generally homogeneous and mechanically sound marble matrix, with no evidence of major low-velocity anomalies attributable to significant internal fracturing or voids.

The GeoTomCG inversion produced a satisfactory final misfit between the measured and calculated travel times, considering the low noise level of the dataset, but also taking into account the complexity of the statue's geometry. After reinterpolation of the model mesh by constraining it to the photogrammetric mesh, the resulting 3D velocity model showed a predominantly homogeneous internal distribution (Fig. 5). Most of the reconstructed volume is characterized by velocities exceeding 3000 m/s, consistent with the hypothesis of a compact marble free of widespread fracturing or significant internal decohesion. Volumetric analysis revealed an almost complete absence of anomalies at velocities below 1500–2000 m/s, which would typically indicate severe degradation, hidden cavities, or through fractures.

The transposition of the NDT geophysical data into an Augmented/Mixed Reality environment (Fig. 6) allowed us to interactively obtain cross-sections of the statue's interior, with coordinates and orientation customizable by the user in order to selectively explore the different parts of the statue and highlight any anomalous areas, visually superimposing them on the visual reality.

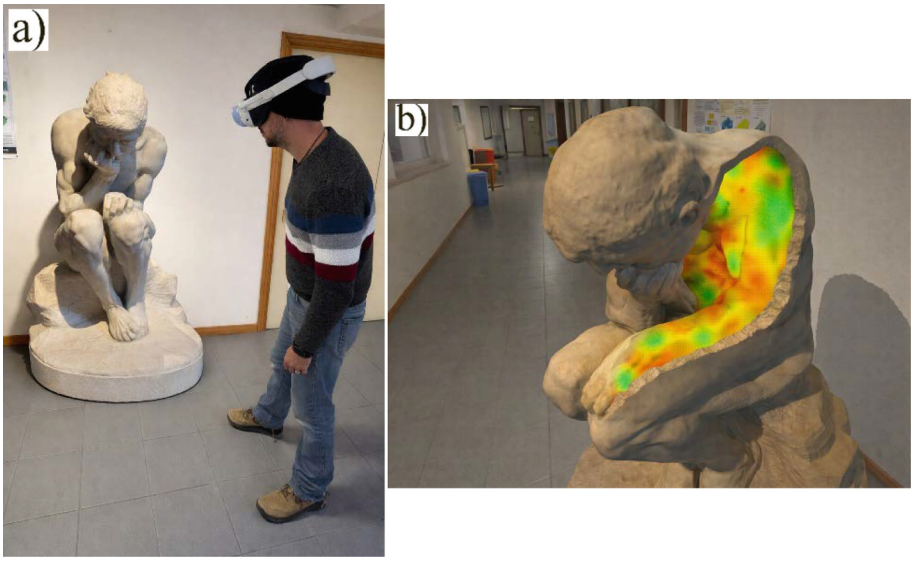


Fig. 6. Mixed Reality visualization of the tomographic model. a) third-person view shows the user observing the statue through the MR headset. b) the corresponding first-person view enables real-time inspection of the statue's internal anomalies, directly superimposed within the 3D model.

5 Conclusions

The present study shows that ultrasonic tomography can provide useful structural information on complex marble sculptures when the tomographic reconstruction is interpreted under an explicit geometric constraint. In the investigated case, the combination of ultrasonic travel-time inversion and photogrammetric modelling made it possible to obtain a three-dimensional velocity distribution that is more consistent with the true volume of the artefact and therefore more reliable for diagnostic interpretation. The main methodological point emerging from the study is not simply the use of photogrammetry alongside tomography, but the use of the photogrammetric mesh as a geometric reference for filtering the regular-grid inversion output. This step is particularly relevant for sculptures and other heritage objects with irregular morphology, where the computational grid extends beyond the actual material boundaries and may introduce non-physical features near the model edges. By removing the external portion of the reconstructed domain, the final model becomes easier to interpret and less exposed to boundary-related artefacts. For the statue *Caino*, the constrained velocity model indicates an overall condition of

internal continuity. The mean ultrasonic velocity is close to 5000 m/s, most of the reconstructed volume shows values above 3000 m/s, and no significant anomalies attributable to through-going fractures, internal cavities, or major degradation zones were detected. Within the limits of the acquisition geometry and tomographic resolution, these results support an interpretation of general structural soundness. These findings do not replace the need for appropriate conservation, transport, and handling protocols. They do, however, provide an objective internal diagnostic basis for evaluating the structural condition of the sculpture in view of possible movement. More generally, the procedure presented here may be applied to other stone artworks whenever tomographic inversion is performed on a regular grid but the investigated object has a non-regular geometry. Finally, integrating the tomographic model into a Mixed Reality framework allowed for a 1:1 scale visualization of the artwork, yielding a significantly enhanced perception of both the artifact's physical proportions and the 3D spatial distribution of the diagnostic results.

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