# A Digital Geometric Comparison Between a 'Vegetal Architecture' and its *Maquette*: the Pincio Promenade and the *Plastico di Roma*

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**Keywords:** Vegetal Architecture, Integrated Digital Survey, Maquette, Hybrid Laser Scanner, Colourimetric Calibration, Geometric Comparison.

## Abstract

This research addresses the enhancement of outdoor Cultural Heritage by exploring innovative methods for integrating different digital models applied to external environments, with a specific focus on so-called 'Vegetal Architectures'. These spaces, shaped by the interaction of natural and built elements, embody historical processes of continuous transformation and therefore require survey methodologies capable of combining material data with the reconstruction of the site's evolutionary history. Among the case studies examined, the Pincio Promenade in Rome plays a central role. Designed by Giuseppe Valadier from 1810, it represents one of the most significant nineteenth-century urban interventions in the city. Despite its cultural relevance, existing graphic documentation remains fragmented and inadequate for an accurate architectural-scale description of its metric and geometric features. A key historical reference is the *Plastico di Roma da Piazza del Popolo a Piazza Colonna con il Pincio*, a *maquette* made by Tommaso Falcetti under Valadier's supervision from 1822, which provides a valuable topographical record of the area. The study aims to produce a detailed digital survey of the Pincio Promenade through the integration of Terrestrial Laser Scanner (TLS) and Simultaneous Localization and Mapping (SLAM) technologies, generating numerical discontinuous and continuous models suitable for the analysis of Vegetal Architectures. In parallel, a high-resolution digital reconstruction of the *Plastico di Roma* is developed using colour-calibrated Structure from Motion (SfM) photogrammetry and hybrid laser scanning. The resulting models are then compared to validate the contemporary survey and to investigate the historical transformations of the garden.

## 1. Introduction

This paper[1] derives from a research project focused on innovative strategies for connecting and integrating heterogeneous digital models in outdoor contexts, with the aim of enhancing Cultural Heritage's external environments. Particular attention is devoted to so-called 'Vegetal Architectures' (Ernouf, 1886, Boriani and Scazzosi, 1992, De Carlo and Paris, 1998), in which the interaction between nature and built components offers distinctive opportunities for digital interpretation. These hybrid spaces possess strong historical significance, as they embody continuous processes of transformation over time. In such contexts, a survey can be considered comprehensive only when it extends beyond the acquisition of material data, incorporating the site's evolutionary trajectory from its original design through subsequent modification to its current configuration. Among the investigated case studies of this research project[2], the Pincio Promenade in Rome (Figure 1a-c) represents a particularly relevant example. Completed between 1811 and 1823, it forms part of a series of major urban projects conceived by Giuseppe Valadier in Rome in the early nineteenth century (Manari, 1996). The project originated in 1810, when the Napoleonic Administration promoted the integration of *Piazza del Popolo* into a system of public gardens connecting the square to Pincio Hill. Valadier proposed a terraced layout, articulated by an ascent that connects multiple levels across an overall height difference of approximately 35 m (Hoffmann, 1967). Despite its importance, the Promenade is documented by a surprisingly limited number of graphic sources capable of rigorously conveying its metric and geometric features at an architectural scale. The extant corpus of Valadier's drawings related to the Pincio Promenade can be classified into three main groups: 1) sketches from his notebooks, lacking precise geometric data and conceived as theoretical and preliminary studies; 2) urban-scale plans, sections, and elevations that necessarily omit architectural detail; 3) architectural or detail-scale drawings (freehand or technical) that depict only isolated portions of the complex, often not reflecting its final configuration (Hoffmann, 1967, Debenedetti, 1979). Consequently, metrically reliable representations of the Promenade as a whole exist only at the urban or territorial scale, generally derived from topographic surveys or remote-sensing data, such as the Numerical Regional Technical Map of Lazio (Regione Lazio, 2026). Within this context of scarce detailed documentation, a particularly significant historical source is the

[1] The authors participated equally in the experimental phase. In writing the article, L.P. was responsible for the Introduction and Conclusions, G.C. for paragraph 2 (Literature Review), L.M. for paragraph 3 (Methodology), and M.L.R. for paragraph 4 (Experiments and Results).

[2] This paper stems from the research project *Information modelling systems for the knowledge, preservation and management of historic gardens and parks*, conducted by the Department of Civil, Building, and Environmental Engineering (DICEA) and the Department of History, Representation, and Restoration of Architecture (DSDRA) at Sapienza University of Rome.

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-2-W12-2026-367-2026 |  


Figure 1. The terraces of the Pincio Promenade seen from the eastern edge of *Piazza del Popolo* (a), near the base of the *Fontana della Dea Roma* (b), and at the level of the second hairpin bend on *Viale Gabriele D'Annunzio* (c). *Plastico di Roma* (d), by Tommaso Falcetti and Giuseppe Valadier. Planimetric diagram of Rome's *Tridente* (e) highlighting Valadier's works that were actually built (in black) and those that were demolished or never built (in bright blue) – graphic elaboration by the authors (source: Manari, 1996).

*Plastico di Roma da Piazza del Popolo a Piazza Colonna con il Pincio*, initiated by Tommaso Falcetti under Valadier's supervision and left unfinished around 1826 (Figure 1d). This *maquette* in cork, wood, plaster, and paper painted with watercolours is now housed in the *Museo di Roma* at *Palazzo Braschi* (Pietrangeli, 1971). It constitutes a valuable topographical record of the area encompassing *Porta del Popolo*, the Pincio Hill, *Piazza Colonna*, and the River Tiber (Roma – Sovrintendenza Capitolina ai Beni Culturali, 2021). Owing to the temporal overlap between its production and the realisation of the Promenade, the *Plastico* can be interpreted as a hybrid source, combining documentary value with the representation of an intermediate design hypothesis. In light of this ambivalence, the research proposes a high-resolution digital survey of the *maquette*, specifically aimed at comparison with the current configuration of the Promenade. The study therefore pursues four main objectives: 1) to digitise the Pincio Promenade using Terrestrial Laser Scanner (TLS) and Simultaneous Localisation and Mapping (SLAM) system, exploiting the latter's suitability for elongated and articulated environments while reducing interference from vehicles and pedestrians; 2) to reconstruct the *Plastico* through Structure from Motion (SfM) photogrammetry and close-range 3D hybrid laser scanning, ensuring high geometric accuracy and surface detail; 3) to compare the two digital reconstructions of the *maquette* in order to evaluate the relative performance of image-based and range-based approaches in capturing metrically reliable geometries; 4) to compare the hybrid laser survey of the *Plastico* with the TLS and SLAM dataset of the Promenade, correlating the historical representation with the current state on a consistent metric basis.

## 2. Literature Review

The digital surveying of *maquettes* is a well-established research field, initially characterised by the integration of multiple techniques. A seminal example is the survey of Antonio da Sangallo the Younger's wooden model for St. Peter's New *Basilica* in Vatican, conducted by the Dept. of Survey, Analysis, and Drawing of Sapienza University of Rome, where the geometric accuracy of TLS was complemented by photogrammetry and direct measurements (Bianchini, 2007). This multimethod approach responded both to the need for data validation and to the limitations of laser scanning in texture acquisition. With technological advances, image-based methods – particularly following the diffusion of SfM photogrammetry – have gained prominence due to their improved texture rendering capabilities and affordability. This has led researchers to favour these techniques for *maquette* surveys, limiting laser scanning to supporting roles, primarily for geometric validation or global referencing. Representative examples includes the reconstruction of a Venetian *galea* based on *maquette* surveys (Balletti et al., 2020), the study of Luigi Ferdinando Marsili's fortification models for documentation and dissemination (Bartolomei et al., 2022), and the creation of a mixed-reality model from Michelangelo's wooden *maquette* for the facade of San Lorenzo in Florence (Bertocci et al., 2024). In some cases, surveys rely almost exclusively on SfM, as demonstrated by Spallone et al. in their study of Carlo Mollino's Turin Horse Racing model, whose real counterpart was demolished in 1960 (Spallone et al., 2021). Nevertheless, urban *maquettes* pose significant challenges for both laser scanning and photogrammetry due to lighting constraints and mutual occlusions between building elements. An exceptional case is the nineteenth-century *Grande Plastico di Pompei* (1:100 scale), whose size required dedicated scaffolding and controlled LED illumination for zenithal photogrammetric acquisition (Malfitana et al., 2016, Malfitana et al., 2020). Despite this body of research, studies specifically addressing *maquettes* that include representations of vegetal elements remain scarce, if not entirely absent.

## 3. Methodology

This section first addresses the main challenges encountered during the survey of the Pincio Promenade and the *Plastico di Roma*, and then explains our methodological solutions.

### 3.1 Integrated Digital Survey of the Pincio Promenade

Surveying operations of the Pincio Promenade began in 2022 with an initial series of massive acquisition campaigns along the hairpin bend formed by *Viale Gabriele D'Annunzio* and *Viale Mickiewicz*, corresponding to the southernmost portion of the point cloud. These acquisitions were performed using a FARO Focus 3D X 130 TLS (FARO Knowledge Base, 2025b). One of the principal challenges encountered during this phase was interference from vehicular and pedestrian traffic, given the centrality of the Pincio Hill and Piazza del Popolo within Rome's cultural landscape. In spring 2024, a second and more extensive survey phase was conducted, covering the remaining portion of *Viale Gabriele D'Annunzio*, including the adjacent gardens, as well as the terraces connecting *Piazza del Popolo* to the Pincio Terrace. Alongside additional TLS acquisitions, three scanning trajectories were performed using a GeoSLAM ZEB Horizon mobile laser scanner (FARO Knowledge Base, 2025a): one along the initial winding section of *Viale Gabriele D'Annunzio* from *Piazza del Popolo*, and two across the gardens located north and south of the Pincio Terrace. SLAM-based systems are particularly suited to elongated and articulated environments, such as serpentine roads and stairways (Cianci et al., 2025, Warchoł et al., 2023), enabling rapid data acquisition while minimising risks to equipment and interference with traffic and pedestrians. As expected, the dense tree canopy hindered georeferencing during SLAM acquisitions, a limitation consistently observed in vegetated contexts. Overall, the surveyed area covered approximately 35,000 m². Due to the considerable computational resources required to process each acquisition, all point clouds were registered in JRC Reconstructor (Gexcel Srl, 2025), where initial noise filtering was applied during import while preserving the original point density reported in Table 1. Manual pre-alignment and fine registration were then performed using the Iterative Closest Point (ICP) algorithm, achieving a maximum alignment error of 0.0476 m. Although duplicate points are automatically removed during import, this operation was repeated on the aligned datasets prior to merging. To address differences in instrumental and effective resolution between TLS and SLAM data, density levelling was applied during merging, enforcing a minimum point spacing of 10 cm and retaining, within each cell, the point with the highest confidence value. Despite these automated cleaning procedures, the merged cloud still contained extraneous elements unintentionally captured during acquisition, such as pedestrians, animals, vehicles, and micro-mobility devices. The dataset was therefore exported in E57 format and further processed in CloudCompare (CloudCompare, 2025), where manual cleaning was conducted by sequentially slicing the cloud: first into 20 sections using planes parallel to the entrance of *Viale del Muro Torto* at *Piazzale Flaminio*, and subsequently into 10 sections using planes perpendicular to the local z-axis. Automatic classification algorithms were deemed unsuitable for two main reasons. First, the dense interpenetration of built structures and vegetation within the Pincio Promenade complicates any classification based on elevation profiles.

| Scanned sector | Type of laser scanner | No. of points |
|---|---|---|
| Southern turn | TLS | 8,039,905 |
| Terraces | TLS | 3,981,445 |
| Southern garden | SLAM | 7,779,892 |
| Northern garden | SLAM | 9,235,040 |
| Serpentine ascent | SLAM | 7,974,004 |
| TOTAL | | 37,010,286 |

Table 1. Points contained in each cloud of the Pincio Promenade's survey after initial filtering by JRC Reconstructor, in correspondence to the scanned sector.

Second, foliage movement during acquisition introduced colour inconsistencies – often exhibiting sky-related hues – that prevented reliable colour-based segmentation. Consequently, the point cloud was manually classified, separating trees and shrubs from terrain and built elements (Figure 2a-b). This phase also included additional manual cleaning, resulting in a final dataset comprising 13,836,644 points.

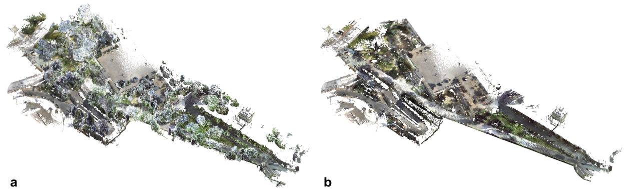


Figure 2. Point cloud of the Pincio Promenade as integration between TLS and SLAM, with vegetation (a) and without (b).

### 3.2 Challenges in the Digital Survey of the *Plastico di Roma*

Following a preliminary inspection conducted on 4 December 2025, the *Museo di Roma* imposed two conditions for the survey of the *Plastico di Roma*: complete avoidance of any physical contact with the *maquette*, and execution of all survey activities exclusively on museum closing days, within maximum time slots of approximately 7.5 hours. Consequently, survey operations were carried out on 15 and 22 December 2025. As is common with urban *maquettes*, the *Plastico* presents significant challenges for indirect sensing techniques, primarily due to shadowed areas affecting roads, alleys, and terrain, generated by the dense arrangement of building and tree models. Beyond these inherent difficulties, the case study exhibited several additional critical issues. First, despite its relatively limited size and a scale comparable to standard urban-planning models, the *maquette* displays an exceptionally high level of detail, including street furniture elements. Second, over more than a century, the *Plastico* has undergone various forms of deterioration, such as fractures in the cork base representing the ground and the River Tiber, detachments between paint layers and substrate, and deformations of individual tree models. In parallel, the original paintwork and surface finishes have faded, resulting in a reduced chromatic range. These conditions persist because, although the *maquette* has been periodically cleaned, it has never undergone a full restoration campaign. A further complication arose from the exhibition layout in which the *Plastico* was displayed during the survey period. The *maquette* was installed within a thematic exhibition featuring parquet flooring and lilac-coloured fittings, including the pedestal supporting the model, while the lighting system produced pronounced cast shadows across the room. To mitigate shadowing effects, two LED lamps were positioned at diametrically opposite locations with respect to the *maquette*. Nevertheless, the combined reflection from the parquet flooring and the coloured exhibition fittings introduced a pervasive olive-toned colour cast in the photographic imagery, requiring specific corrective measures during the photogrammetric acquisition.

### 3.3 *Plastico di Roma*: Hybrid Laser Scanning

The technological evolution of handheld scanners, especially after the emergence of structured light scanners, has introduced new close-range sensing techniques capable of overcoming the difficulties encountered by TLS, such as laser shadows and poor texture capture and rendering (Merella et al., 2023). The first survey technique adopted for the *Plastico di Roma* employed a 3DeVOK MT handheld hybrid laser scanner, equipped with three types of light sources: 34 blue laser lines, 22 infrared laser lines, and infrared Vertical Cavity Surface Emitting Laser (VCSEL) structured light. It is also equipped with a texture camera. The variety of sensors featured in the 3DeVOK MT allows scanning distances ranging from 150 to 1000 mm for all three light sources, reaching a maximum of 1500 mm exclusively for structured light speckle (3DeVOK, 2022). The *maquette*'s sensing process (Figure 3a-c) included a preliminary start-up and setup phase, consisting of reaching an operating temperature equal and not exceeding 40°C, and calibration using a specific target and a dedicated software, named 3DeVOK Studio.

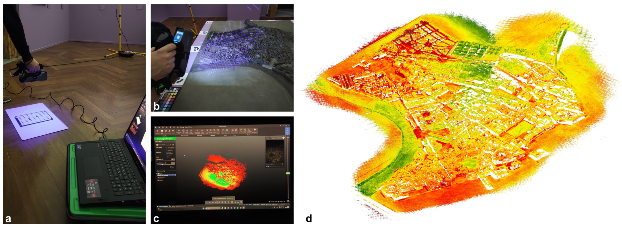

Figure 3. Survey of the *Plastico* with hybrid laser scanner: a) calibration and warming up; b) sensing the *maquette* with blue laser lines; c) real time point cloud generation in 3DeVOK Studio; d) point cloud generated from the acquisition.

Hybrid laser scanners work best when specific markers are applied to the object being sensed, but we must remember that the *maquette* could not be subject to direct contact. However, the 3DeVOK MT scanner can align acquired data without markers, using surfaces rich in geometry and colour details of the object being surveyed as a reference. We therefore took advantege of the self-orienting capabilities of the instrument to generate point clouds with continuity, even though we had planned to carry out the acquisition over two non-consecutive days. However, we found that the device had difficulty maintaining proper tracking when scanning areas characterised by low geometric complexity and substantial chromatic uniformity, resulting in data noise or, in more critical cases, misalignments between consecutive point clouds. Real-time detection of such misalignments allowed us to immediately retrace the acquisition path and continue scanning along more clearly distinguishable geometries. Consequently, the final point cloud includes only the 'built' portion of the *Plastico* and does not contain any survey data related to the edges of the supporting base (Figure 3d).

### 3.4 *Plastico di Roma*: Colour Calibrated Structure from Motion Photogrammetry

In addition to the LED lamps used for room illumination, the photogrammetric survey employed an Olympus EM-10 camera with Panasonic Lumix G 25mm f/1.7 ASPH lens, operated via a Wi-Fi-connected digital tablet; a Manfrotto 055 aluminium 3-section tripod with an adjustable vertical/horizontal column and a Manfrotto 808RC4 3-way pan/tilt tripod head (with RC4 quick release plate); cardboard encoded targets for materialisation of Ground Control Points (GCPs); a Mark.08 colourimetric target from Profilocolore Srl. The meticulous detail characterising the *maquette* required us to make the most of our equipment and the SfM technique, forcing us to carefully plan the photogrammetric survey. We based our Ground Sampling Distance (GSD) calculation on the maximum shooting distance expected during acquisition, which was the length of the segment connecting the projection centre of the camera, placed at the maximum height reachable by the tripod and at one of the vertices of the *Plastico*'s pedestal, and the opposite vertex with respect to the diagonal of the upper base of the pedestal itself, i.e. 2262 mm (Figure 4a-b). A summary of the parameters used in the photogrammetric survey's project is shown in Table 2. Before the first acquisition on 15 December, we took photos of a checkerboard target for a lens calibration procedure programmed for a second stage. The need to carry out the photogrammetric acquisition over two non-consecutive days, without possibility of fixing even temporary markers, forced us to arrange two sets of 16 encoded targets each alternately, for a total of 32 GCPs to be used during SfM processing.

| | |
|---|---|
| **Focal length** | 25 mm |
| **Pixel size** | 0.0037 mm |
| **Shooting distance** | 2262 mm |
| **GSD constrained by the setup** | 0.3348 mm |
| **Width of the frame projected horizontally onto the maquette** | 1574 mm |
| **Height of the frame projected horizontally onto the maquette** | 1176 mm |
| **Horizontal baseline** | 630 mm |
| **Vertical baseline** | 235 mm |

Table 2. Point cloud statistics during SfM processing.

We materialised half of these GCPs during the survey operations on 15 December, while the other half were materialised for the acquisition on 22 December. The main reason for choosing such a high number of GCPs was that we were unable to check the positioning with trilateration, as we could not use adhesives or touch the *Plastico*. However, we tried to place the targets as carefully as possible (Figure 4c).

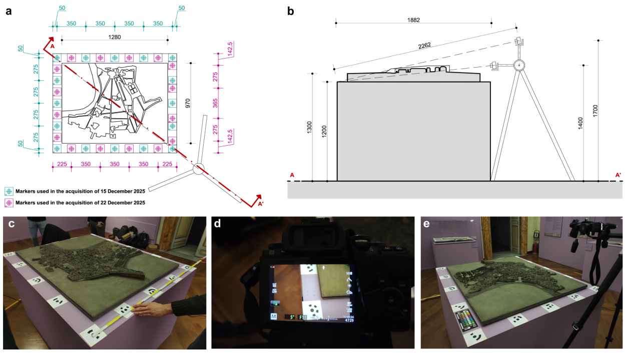

Figure 4. Colour calibrated SfM: plan (a) and oblique section A-A' (b) of the photogrammetric project; encoded target placement (c); camera setup (d); view of the scene (e).

We also placed the Mark.08 colourimetric target on the pedestal, subjecting it to the same lighting as the *maquette*. Camera settings (Table 3) were the result of a compromise between the need to reduce noise, avoid overexposing the image, and achieve a depth of field that would bring as much of the model as possible into focus within the frame. Therefore, in addition to controlling the camera via Wi-Fi, we set a timer to manage the slow shutter speed, assuming a waiting time compatible with the damping of the tripod's oscillations after each movement and orientation (Figure 4d-e).

| Aperture | Shutter speed | ISO | Colour space |
|---|---|---|---|
| F11 | 5” | 100 | Adobe RGB |

Table 3. Camera settings for the photogrammetric survey.

We divided the photogrammetric survey into 7 sequences of photographs taken while circling the model: 5 captured on 15 December; 2 captured on 22 December. To ensure a good level of detail on the vertical walls of the outermost building models, we took a sequence of photographs with horizontal optical axes, making an exception to the vertical coverage required by photogrammetric planning. However, the photogrammetric project is approximately respected in the other sequences (Figure 5).

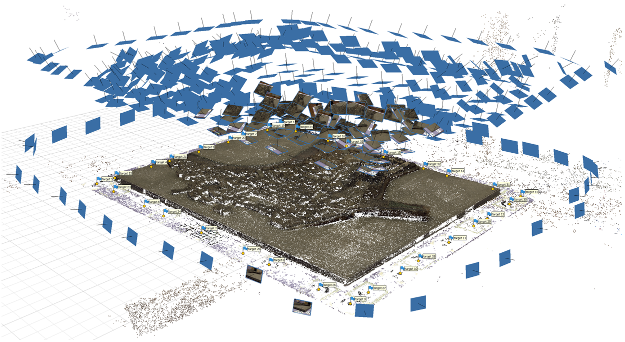

Figure 5. Image alignment and sparse cloud of the *Plastico* during SfM processing in Agisoft Metashape environment.

To mitigate chromatic alteration caused by light reflected from the surrounding environment, we used a colourimetric calibration method derived from analysis and digitisation techniques in the field of artistic heritage conservation (Carnevali et al., 2021). All RAW files underwent colourimetric calibration using Visipick software by Profilocolore Srl, in conjunction with demosaicing. This program compares the spectral data of the Mark.08 target in each image with laboratory-measured reference values under $D_{65}$ illuminant, a standard by Commission Internationale de l'Éclairage (CIE), which represents approximately the average midday light from the northern sky (Commission Internationale de l'Éclairage, 1999, Lee, 2005). $D_{65}$ is also known as the daylight standard illuminant, as it includes direct solar light and light diffused by a clear sky. We had Visipick analyse a RAW file in Adobe RGB colour space framing the Mark.08 colourimetric target under the same lighting conditions as the *Plastico*. The colourimetric characterisation algorithm evaluated the deviation between the spectral data of the target in the image and the spectral data of the same target under $D_{65}$ illuminant (reproduced by Profilocolore Srl in the laboratory) stored in its code, based on CIE 2000 Formula (Oleari, 2016, Lindbloom, 2017) and expressing a colour error parameter value $\Delta E_{00}$ equal to 1.89. Considering this value acceptable, we applied this colourimetric calibration to all RAW files, saving them as 16-bit TIFFs in Wide Gamut RGB colour space (Figure 6a-b). The software carried out non-linear colourimetric transformations based on CIE 64 Colour Matching Functions (CMF) (Oleari, 2016), statistically reconstructing all colours present in Wide Gamut RGB colour space but not included in the Adobe RGB one (Carnevali et al., 2021). In this way, in addition to correcting the colour alteration, the procedure improved the sharpness of the images (Figure 6c-d). SfM processing was carried out in Agisoft Metashape software. Intrinsic and extrinsic camera parameters were calculated from specifically colour-characterised images for lens calibration to ensure consistency with the actual survey images. After excluding blurred frames, 419 sharp images were selected and divided into 7 sequences. Incorporating 32 GCPs, images were aligned at maximum precision, generating 7 sparse point clouds. Alignment and merging were performed using both point- and target-based methods, with target-based alignment providing superior results due to the abundant GCPs. A dense point cloud was then generated in 'High' quality with 'Mild' filtering and then

Figure 6. Colour calibrated SfM: the Mark.08 colourimetric target in one of the photos, before (a) and after (b) colourimetric calibration; detail of the *Plastico*'s Pincio Hill before (c) and after (d) calibration; the colour calibrated point cloud (e).

manually cleaned to preserve maximum detail, without applying additional automated filtering (Figure 6e). A summary of point cloud processing statistics is provided in Table 4.

| Point cloud | No. of images | No. of points |
|---|---|---|
| Sequence 1 | 42 | 77,823 |
| Sequence 2 | 47 | 76,995 |
| Sequence 3 | 38 | 70,210 |
| Sequence 4 | 44 | 65,868 |
| Sequence 5 | 44 | 74,870 |
| Sequence 6 | 160 | 304,493 |
| Sequence 7 | 44 | 92,262 |
| Merged sparse cloud | 419 | 762,521 |
| Raw dense cloud | 419 | 188,907,819 |
| Cleaned dense cloud | 419 | 153,365,557 |

Table 4. Point cloud statistics during SfM processing.

## 4. Experiments and Results

We now expose our comparison of the two digital models in terms of geometry and dimensions, carried out with the dual objective of validating the contemporary survey of the Promenade against the historical *maquette* and facilitating a detailed analysis of the transformations that shaped the garden over time.

### 4.1 Comparison of Digital Models of the *Plastico di Roma*: Structure from Motion and Hybrid Laser Scanning

The first experiment focused on a metric and geometric comparison between two digital models of the *Plastico di Roma*, obtained via hybrid laser scanning and SfM photogrammetry. The objective was to assess geometric consistency between the datasets and analyse deviation patterns, highlighting strengths and limitations of each method when applied to an urban *maquette* with high formal complexity and extensive miniature vegetation. Results, visualized on the SfM model with the hybrid laser scanning model as geometric reference due to its higher metric stability and lower noise, were computed in CloudCompare. Following alignment via the ICP algorithm, a cloud-to-cloud (C2C) comparison calculated absolute distances between corresponding points within a maximum threshold of 5 mm. Deviations were manually adjusted for visual contrast using a 256-step Blue-Green-Yellow-Red colour scale limited to 0÷3 mm. Points lacking correspondence in the hybrid model, mainly in homogeneous regions such as smooth base areas, were excluded and displayed in grey from 4.9 mm. The histogram of global C2C deviations (Figure 7c) shows a distribution strongly concentrated around 0, indicating overall geometric conformity. Most deviations fall within a narrow interval consistent with the *maquette*'s scale and expected acquisition uncertainties. Larger deviations, beyond 3 mm, correspond primarily to geometric discontinuities, shadowed areas, or surfaces challenging for SfM reconstruction, including vegetated volumes and thin vertical edges. To further analyse deviations, C2C distances were decomposed along the Cartesian axes. The z-axis histogram (Figure 7f) reveals a distinct pattern compared to the global distribution. Within ±5 mm, results were manually adjusted using the same colour scale, limited to ±4 mm. This analysis suggests that hybrid laser scanning provides greater vertical stability, whereas SfM is more sensitive to localized errors in inclined surfaces, vegetation (e.g., tree canopies), and irregular ground planes, with illumination and occlusions further affecting triangulation accuracy. Overall, both global and vertical deviation analyses confirm good geometric correspondence between the models, while highlighting critical issues in vegetated and non-planar areas. Qualitatively, SfM delivers more continuous surface representation and accurate colour information due to high point density and calibrated imagery. Conversely, the hybrid model offers stable, low-noise geometries, making it a reliable metric reference despite localized gaps and reduced radiometric detail. The comparison underscores the complementarity of the approaches, supporting the use of the laser-based model as a benchmark for SfM validation.

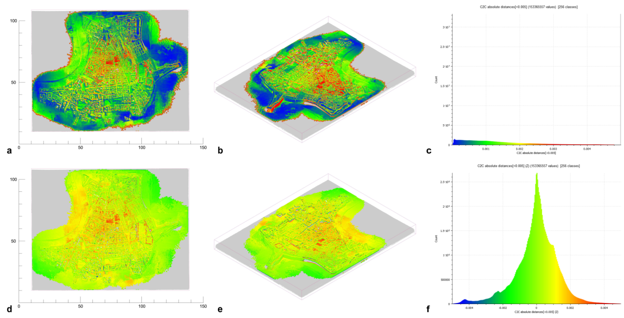

Figure 7. C2C comparison of the hybrid laser and colour calibrated SfM point clouds: results of the absolute distances calculation in top view (a) and 3D view (b), along with the histogram of global C2C deviations(c); results of calculation of distance components along the z-axis in top view (d) and 3D view (e), along with the histogram of z-axis C2C deviations (f).

## 4.2 Comparative Study of the Historical *Maquette* and Contemporary Survey of the Pincio Promenade

The second experiment extended the comparison from the intra-object level (*maquette versus maquette*) to an inter-scalar analysis, correlating the historical *Plastico* reconstructed via SfM with the contemporary survey of the Pincio Promenade obtained through integrated TLS and SLAM acquisitions. This step constitutes the core interpretative focus of the study, aimed at evaluating the correspondence between the historical *maquette* and the current garden configuration, as well as identifying discrepancies arising from design intent or construction phases. To ensure comparability, the structured numerical model of the Pincio was scaled and aligned to the reference system of the hybrid *Plastico* survey, using architectural features that have remained largely unchanged, including the *Fontana della Dea Roma* in *Piazza del Popolo* and several perimeter buildings. Alignment relied solely on homologous point recognition, as ICP refinement in CloudCompare was unfeasible due to the lack of geometrically homogeneous areas in both models. To facilitate the C2C comparison, all vegetation above street and ground levels was removed (Figure 8a), as these elements represented the main source of noise in the TLS-SLAM cloud and were inherently inconsistent with the *maquette*. As in the first test, the C2C comparison allowed calculation of absolute distances between corresponding points, within a maximum threshold of 10 mm. Results were manually adjusted for visual contrast using a 256-step Blue-Green-Yellow-Red scale limited to 0÷5 mm. The analysis revealed substantial planimetric coherence between the *Plastico* and the current Promenade layout, confirming the *maquette*'s high documentary value. Significant altimetric and volumetric differences, however, emerged along terraced slopes and densely vegetated areas, where the historical *Plastico* exhibits simplified – and in some cases markedly divergent – profiles compared to the contemporary survey. This suggests that the portion of the Pincio represented in the *maquette* corresponds to an intermediate or partially unrealized design phase. These geometric discrepancies cannot be attributed solely to representational or scaling errors; rather, they reflect the hybrid nature of the *Plastico*, positioned between a record of the existing state and a design-oriented artefact. Accordingly, the comparison between the hybrid model and the TLS-SLAM survey goes beyond metric validation, serving as a critical tool for interpreting the garden's historical evolution and for identifying continuities, adaptations, and subsequent transformations.

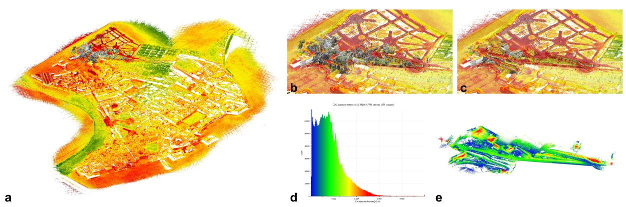

Figure 8. Comparison between the TLS-SLAM point cloud of the Pincio Promenade and the Plastico's hybrid laser point cloud: 3D overview alignment of the two point clouds (a); close-up on the Pincio Promenade, with the vegetation of the TLS-SLAM point cloud (b) and without (c); results of the absolute distances calculation in the histogram of global C2C deviations (d) and in 3D view (e).

## 4.3 Textured Numerical Continuous Model of the *Plastico di Roma*

The study involved the computation of a mesh in Agisoft Metashape's environment, starting from the clean dense point cloud obtained via SfM. We carried out processing in 'High' quality mode, yielding a mesh composed of 30,673,111 faces. Subsequently, we applied 4 texture maps, each measuring 8,192 × 8,192 px (Figure 9a-d). Finally, we generated a top-down orthophoto of the textured mesh, with a resolution of 4,096 × 3,153 px and 0.321 mm/px (Figure 9e). According to the Agisoft Metashape User Manual, the software does not alter the colour data of imported images (Agisoft LCC, 2021), therefore the chromatic properties of the Visipick-calibrated images remained unchanged across all produced digital models, as confirmed by direct inspection of the point cloud, mesh, and orthophoto files. The orthophoto enabled a preliminary estimation of the *Plastico*'s scale in relation to the *Tridente*'s area, based on the comparison of distances between reference points which remain unchanged in reality (pinpointed in QGIS via georeferenced satellite orthophotos) and are also represented in the *maquette* – for example, the distance between the obelisk

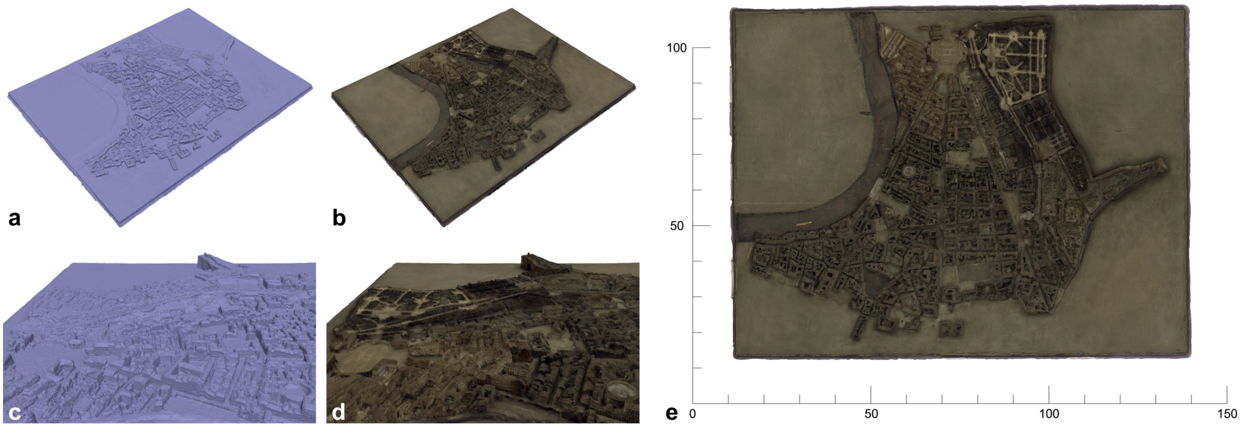


Figure 9. Numerical continuous model of the *Plastico*: 3D view of the mesh with uniform surface (a) and textures (b); detail of the Pincio Hill with uniform surface (c) and textures (d); top view ortophoto of the mesh (e).

in *Piazza del Popolo* and the southwestern corner of *Palazzo Borghese*. On a sample of 12 measurements, an average scale ratio of approximately 1:1946.73 was calculated, with a variance of $\rho = 469.50$ and a standard deviation of $\mu = 21.67$.

## 5. Conclusions

Thanks to the comparison between the georeferenced satellite orthophotos of the *Tridente*'s area and the SfM-generated orthophoto of the *Plastico*, we tentatively estimated the latter's scale of representation at approximately 1:1946.73. Considering the historical context of its construction, it is reasonable to assume that Falcetti employed a unit of measurement different from the modern metric system when calculating the scale ratio between the *Tridente*'s area and his *maquette*. Future research could explore the construction process of the *Plastico* in greater depth, including an analysis of Falcetti's drawings and sketches of the *Tridente*, which are kept in the *Museo di Roma* (Fondo Falcetti, Mob. DP, cass. 3) (Roma – Sovrintendenza Capitolina ai Beni Culturali, 2021). Such a study could clarify the unit of measurement chosen by Falcetti and the scale ratio he applied in designing the model. The comparative analysis of three-dimensional acquisition and restitution techniques applied to the *Plastico* highlighted specific strengths and limitations of each approach. The hybrid laser scanner demonstrated superior performance in defining the formal geometries of buildings and vegetation, generating point-based models with low noise levels and geometrically consistent shapes. However, this advantage was partly offset by shadowed areas on numerous building facades – mainly due to variations in acquisition timing and manual handling – and by notable gaps in ground surfaces, particularly along narrow streets. Additionally, the hybrid model exhibited lower overall point density and lacked the possibility of colourimetric calibration. Conversely, the SfM methodology, once colour-calibrated, produced denser point clouds and a more detailed surface model, effectively capturing pictorial features. Limitations included higher noise, arising from the alignment of images acquired under differing conditions of sharpness and blur, and challenges in mesh generation for vegetation, a central focus of this study. These drawbacks were compensated by a substantial reduction in shadowed areas, an almost continuous representation of the ground, and a more faithful chromatic rendering with richer textures and minimal colour distortion. Interpretation of the comparative data further confirmed that the maquette represents an unrealized design stage of the final Pincio Promenade, with discernible differences in altimetry, geometry, volume, and spatial organization. Looking ahead, the research could evolve toward a virtual restoration of the *Plastico*, supporting potential physical restoration and reintegration efforts through digital reverse engineering. Such an approach would enhance understanding, preservation, and dissemination of the artifact via its digital counterpart.

## Conflicts of interest

The authors declare that they have no conflict of interest.

## Acknowledgements

The authors acknowledge Sapienza University of Rome for the research funding that supported this work. Gratitude is also extended to the *Sovrintendenza Capitolina ai Beni Culturali – Direzione dei Musei Civici di Roma Capitale* (Capitoline Superintendence for Cultural Heritage – Directorate of the Civic Museums of the Municipality of Rome) for permitting the acquisition and reproduction of data related to the *Plastico di Roma da Piazza del Popolo a Piazza Colonna con il Pincio*, by Tommaso Falcetti and Giuseppe Valadier, kept at the *Museo di Roma* (inventory number MR 44072; request protocol RI/2025/45850) © Roma Capitale. The authors further acknowledge Microgeo Srl for providing the 3DeVOK MT hybrid laser scanner and for conducting the corresponding data acquisition. Finally, thanks are due to Profilocolore Srl for supplying the Mark.08 colourimetric target and Visipick software used for the colour calibration of images in the Structure from Motion processing.

## References

3DeVOK, 2022. Case Studies on 3D Digitization of Cultural Relics. 3DeVOK. https://www.3devok.com/news/case-studies-on-3d-digitization-of-cultural-relics/ (31 October 2025).

Agisoft LCC, 2021. Metashape Professional Edition Software. Version 1.7.

Balletti, C., Guerra, F., Lorenzon, A., 2020. Close range photogrammetry for analyzing distressed trees. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLIII-B2-2020, 1371–1379. doi.org/10.5194/isprs-archives-XLIII-B2-2020-1371-2020.

Bartolomei, C., Morganti, C., Prati, D., 2022. Digital strategies for learning and valorising the models of fortifications by Luigi Ferdinando Marsili. *Dialogues. Visions and visuality. Witnessing Communicating Experimenting. Proceedings of the 43rd International Conference of Representation Disciplines Teachers*, FrancoAngeli, Milan, 107–122.

Bertocci, S., Bigongiari, M., Pasquali, A., 2024. Digitisation of the wooden maquette at Casa Buonarroti: a project never realised for the facade of San Lorenzo in Firenze. *KUI Conference Culture and Computer Science. From Humanism to Digital Humanities (KUI 2024), October 03, 04, 2024, Florence, Italy*, ACM, New York, NY, USA, Paper no. 17.

Bianchini, C., 2007. From reality to virtuality (and back): the wooden model by Antonio da Sangallo for the new St. Peter's in the Vatican. *Disegnare Idee Immagini / Disegnare Ideas Images*, XVIII(34), 36–41.

Boriani, M., Scazzosi, L., 1992. *Il giardino e il tempo: conservazione e manutenzione delle architetture vegetali*. Guerini, Milan.

Carnevali, L., Lanfranchi, F., Martelli, L., Martelli, M., 2021. Colourimetric Calibration for Photography, Photogrammetry, and Photomodelling within Architectural Survey. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLVI-4/W5-2021, 151–158. doi.org/10.5194/isprs-archives-XLVI-4-W5-2021-151-2021.

Cianci, M. G., Botta, S., Calisi, D., Colaceci, S., Ghio, V., Gullotta, A., Schiaroli, M., 2025. UAS, LIDAR, GeoSLAM for 3D Survey of Natural and Cultural Heritage. UAS, LIDAR, GeoSLAM for 3D Survey of Natural and Cultural heritage. *SCIentific RESearch and Information Technology. Ricerca Scientifica e Tecnologie dell'Informazione*, 15(1), 33–46. doi.org/10.2423/i22394303v15n1p33.

CloudCompare, 2025. CloudCompare. 3D point cloud and mesh processing software. Open source project. https://www.danielgm.net/cc/ (31 October 2025).

Commission Internationale de l'Éclairage, 1999. CIE Standard Illuminants for Colorimetry. (ISO 10526:1999/CIE S005/E-1998).

De Carlo, L., Paris, L., 1998. Rilevare il verde. Indirizzi metodologici per la documentazione delle ≪architetture vegetali≫. *Disegnare idee immagini: rivista semestrale del Dipartimento di Rappresentazione e Rilievo*, VIII(17), 33–44.

Debenedetti, E., 1979. *Valadier: diario architettonico*. Bulzoni, Rome.

Ernouf, A. A., 1886. *L'art Des Jardins. Parcs, Jardins, Promenades. Traite pratique et didactique (3e édition entièrement refondue avec le concours de Alphand, A.)*. Typographie Charles Unsinger, Paris.

FARO Knowledge Base, 2025a. Getting Started with ZEB Horizon. Ametek, Inc. https://knowledge.faro.com/Hardware/GeoSlam/ZEB_Horizon_and_Horizon_RT/Getting_Started_with_ZEB_Horizon (31 October 2025).

FARO Knowledge Base, 2025b. Technical Specification Sheet for the Focus Laser Scanner. Ametek, Inc. https://knowledge.faro.com/Hardware/Focus/Focus/Technical_Specification_Sheet_for_the_Focus_Laser_Scanner (31 October 2025).

Gexcel Srl, 2025. Reconstructor. The powerful processing software for LIDAR data. Gexcel Srl. https://gexcel.it/en/software/reconstructor (31 October 2025).

Hoffmann, P., 1967. *Il monte Pincio e la casina Valadier*. Edizioni del Mondo, Stabilimento tipografico Julia, Rome.

Lee, H., 2005. *Introduction to Color Imaging Science*. Cambridge University Press, Cambridge, UK.

Lindbloom, B., 2017. Computing xyz from spectral data (reflective and transmissive cases). http://www.brucelindbloom.com (7 January 2026).

Malfitana, D., Amara, G., Barone, S., Fragalà, G., Pavone, D. P., 2016. Il plastico ottocentesco di Pompei al sorgere della fotografia: un "doppio" archivio 3D? *Quaderni Friulani di Archeologia*, XXVI(1), 211–223.

Malfitana, D., Mazzaglia, A., Amara, G., Fragalà, G., Pavone, D. P., 2020. Modellare la materia per conservare la memoria. Il caso del Grande Plastico di Pompei. *Miniere della memoria. Scavi in archivi, depositi e biblioteche*, All'Insegna del Giglio s.a.s., Sesto Fiorentino, Italy, 63–79.

Manari, E., 1996. Itinerario Valadier e Roma. *Domus*, January 1996(778), 103–104.

Merella, M., Farina, S., Scaglia, P., Caneve, G., Bernardini, G., Pieri, A., Collareta, A., Bianucci, G., 2023. Structured-Light 3D Scanning as a Tool for Creating a Digital Collection of Modern and Fossil Cetacean Skeletons (Natural History Museum, University of Pisa). *Heritage*, 2023(6), 6762–6776. doi.org/10.3390/heritage6100353.

Oleari, C., 2016. *Standard colorimetry. Definitions, Algorithms and Software*. John Wiley and Sons Ltd, Chichester, UK.

Pietrangeli, C., 1971. *Il Museo di Roma: documenti e iconografia*. Cappelli, Bologna, Italy.

Regione Lazio, 2026. Carta Tecnica Regionale Numerica (CTRN) - Scala 1:5.000 - v. 2014. Geoportale. https://geoportale.regione.lazio.it/layers/ctr_5k_retiled:geonode:ctr_5k_retiled (7 January 2026).

Roma – Sovrintendenza Capitolina ai Beni Culturali, 2021. SIMART – Catalogo dei Beni Culturali di Roma Capitale. Plastico di Roma della zona fra piazza del Popolo e piazza Colonna con la collina del Pincio. https://simartweb.comune.roma.it/dettaglio-bene/1830685653 (7 January 2026).

Spallone, R., Bertola, G., Ronco, F., 2021. Digital strategies for the valorisation of archival heritage. *Acta IMEKO*, 10(1), 224–233. doi.org/10.21014/ACTA_IMEKO.V10I1.883.

Warchoł, A., Karaś, T., Antoń, M., 2023. Selected Qualitative Aspects of LIDAR point clouds: GeoSLAM Zeb-Revo and FARO Focus 3D X130. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLVIII-1/W3-2023, 205–212. doi.org/10.5194/isprs-archives-XLVIII-1-W3-2023-205-2023.