

Application of LiDAR Sensors for the Reconstruction of the Production Techniques of Artificial Conglomerate Blocks: the Case of the Maconi Tower – Siena (Italy)

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Abstract:

The Maconi tower, dating back to around the 12th century and belonging to one of the leading families of medieval Siena, is characterised, in its internal and external façades, by a wall made of limestone blocks, reused bricks and large blocks of artificial conglomerate. The latter, the subject of this research and also visible in other buildings in the city, are parallelepiped in shape and are made of mortar and angular stone elements, with a texture that varies depending on the size and shape of the aggregates, as well as the processing of the blocks themselves. The aim of the research was to verify the effectiveness of new three-dimensional survey methodologies for the documentation and morphological analysis of artificial conglomerate blocks, in order to understand the production system of the latter. To this end, the LiDAR (Light Detection and Ranging) technology integrated into Apple iPhone PRO devices was used, with which it was possible to obtain detailed 3D scans with the help of a free application and an electronic stabilizer, all accompanied by measurements with traditional systems (comb profiler), used to verify the method. The study concerned, in particular, the evaluation of the roughness of the external surface of the blocks, or the three-dimensional shape of the external faces, as a possible indicator for understanding the methods of construction and processing. The analysis of the surface texture, obtained through three-dimensional scanning, highlighted two types of surfaces in relation to the variation values between the level of the mortar and the top of the stone elements: the first type shows a significant variation, while the second has a more contained difference, indicating a different degree of irregularity. The investigations conducted allowed us to quantify the roughness of the artificial conglomerate blocks, highlighting variations compatible with different exposure to atmospheric agents and/or different construction methods.

CCS Concepts

•Applied computing ~ Arts and humanities ~ Architecture (buildings) ~ Computer-aided design

1. Introduction

The Maconi tower (c. 12th century) (Figure no. 1), belonging to one of the dominant families of medieval Siena, is located next to the palace of the same name, both entirely incorporated into buildings built in the early modern age, in the centre of the block between via Cecco Angiolieri, via San Virgilio, via delle Donzelle and Banchi di Sotto [Bru21].



Figure 1: location of the Maconi tower, Via Cecco Angiolieri, [Geo25].

On the outside of the structure, now significantly reduced in height, the southern facade (Figure 2a) and part of the side facing west are preserved, while inside the system is visible in almost its entirety (Figure 2b), with the exception of the floor level, modified for the recent installation of a water tank and for a series of cuts in

the walls for the recovery of building materials. Currently the tower reaches a height of 11.00 m and is characterised by the presence of a sloping base which gives it a width, on the outside, of 8.30 m at the base and 5.80 m at the top; the thickness of the walls is approximately 1.87 m. The internal space, of an approximately square shape, has a width of between 2.20 and 2.50 m. The internal and external features are the same building material: “Pietra da torre” and reused parallelepiped elements derived from the cutting of ancient walls characterised by different construction techniques, such as artificial conglomerate, so-called vittata work, brickwork and mixed stone and brick work.

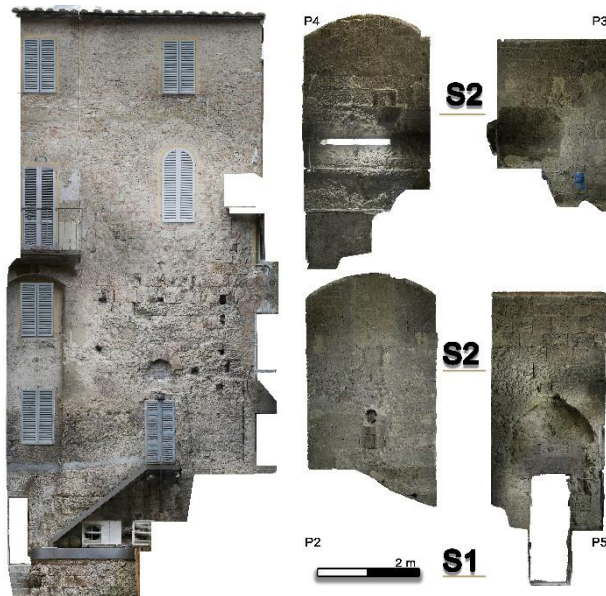
The aim of the contribution is to verify and highlight the effectiveness of new three-dimensional survey methodologies, applied for now to an initial documentation and morphological analysis of the artificial conglomerate blocks. It is believed that these results may be useful, in a subsequent phase of the research, to understand the processing techniques of both the conglomerate blocks and other building materials, even in contexts different from the one being examined.

2. Instruments

2.1. User-friendly photogrammetry

Modern photogrammetry is increasingly accessible due to the integration of advanced, low-cost technologies in everyday devices such as Apple iPhones and iPad Pros. Equipped with LiDAR sensors, originally intended for AR, these devices, when paired

with specific applications (e.g. Niantic Inc, Scaniverse) and three-axis stabilizers [RGG25], are adaptable for generating digital twins in cultural heritage management (Figure n.3 a). This setup was used to scan both the interior/exterior of the tower and the artificial conglomerate blocks [BCY*24]. Post-processing was carried out in CloudCompare to enhance model accuracy. To validate reconstruction fidelity, surface roughness was also assessed using a comb profilometer, as traditional method of survey [SSF24] (Figure n.3 b).



Figures 2 a-b: Orthophoto of the southern facade of the Maconi tower (a) and the four internal walls, obtained through photogrammetry. P4: west front, towards via delle Donzelle; P3: north front, towards via Cecco Angiolieri; P2: east front, towards via di San Vigilio; P5: south front, towards via Banchi di Sotto. [Bru21]

2.1.1. Apple iPhone PRO LiDAR sensor. Since 2020, Apple has integrated compact LiDAR sensors [Sen21] into its high-end devices, enabling indoor and outdoor 3D scanning up to 4.90 m [SCTG21]. Combined with cameras and motion sensors, the system leverages depth mapping and on-chip computer vision to enrich point clouds with accurate spatial and color data.

2.1.2. Niantic Inc, Scaniverse. Scaniverse, developed by Niantic Inc. [Sca25], is a 3D scanning app that leverages the LiDAR sensor on Apple Pro devices to rapidly acquire accurate mesh models of environments, object and surfaces. The outputs, exportable in OBJ, FBX, USDZ or STL formats are compatible with standard 3D post-processing software.

2.1.3. Three-axis stabilizer. The use of a three-axis motorized gimbal is a solution to ensure precision acquisitions by actively compensating for movements along the pan, tilt and roll axes, reducing vibrations and enabling smooth, controlled scans. To enhance performance in low-light conditions, a screw-on LED light can be mounted at the base, providing even illumination, minimizing shadows, and improving surface detail definition, crucial for accurate reconstruction and texture analysis.

2.1.4. Post-processing with CloudCompare software. The acquired 3D model was processed in CloudCompare [Gir25], a point cloud analysis software enabling refinement through key

operations such as resampling, statistical analysis and mesh segmentation. The aim of the research was to generate a high-fidelity digital model optimized for archaeometric analysis of texture and roughness in artificial conglomerate block.

2.1.5. Comb profiler. Surface roughness refers to geometric irregularities of real objects, typically analyzed by sectioning the surface with a plane orthogonal to it, obtaining the actual profile from their intersection. To investigate these features, a comb profilometer was employed, enabling precise detection and comparison of shapes and profiles for correlation between the digital model and the original surface.



Figures 3 a-b: a) Gear setup: Apple iPhone Pro on 3-axis gimbal and LED light; b) acquisition of roughness profiles using the comb profiler

3. Research method

The 3D survey enabled the digital reconstruction of the Maconi Tower, including both the internal architectural volume and the artificial conglomerate blocks. This allowed a detailed investigation of the constituent materials through morphological and textural surface analysis.

The workflow was structured in four phases. First, two different surveys were carried out. A rapid scan was performed by placing the LiDAR-enabled device at the center of the room (approx. 1,25 m from the walls), rotating it clockwise on the horizontal axis, with vertical oscillations using a three-axis stabilizer. This allows for a general geometric acquisition. A second, more detailed scan was then conducted along the perimeter (≈0.80 m from the walls), enabling a higher-resolution survey of the wall surfaces.

The second phase focused on the digital acquisition of 16 individual blocks of artificial conglomerate. These were surveyed through dual acquisition: LiDAR scans produced detailed point clouds, complemented by analogue roughness profiles obtained using a comb profilometer. To align the datasets, a spatial registration process was applied, using CloudCompare's ICP (Iterative Closest Point) algorithm to co-register the LiDAR point clouds with the CAD vectorized profilometric traces, thereby enabling comparative morphometric analysis.

In the third phase, the analogue profiles were digitized in a CAD environment, allowing for comparative analysis with the LiDAR-derived models.

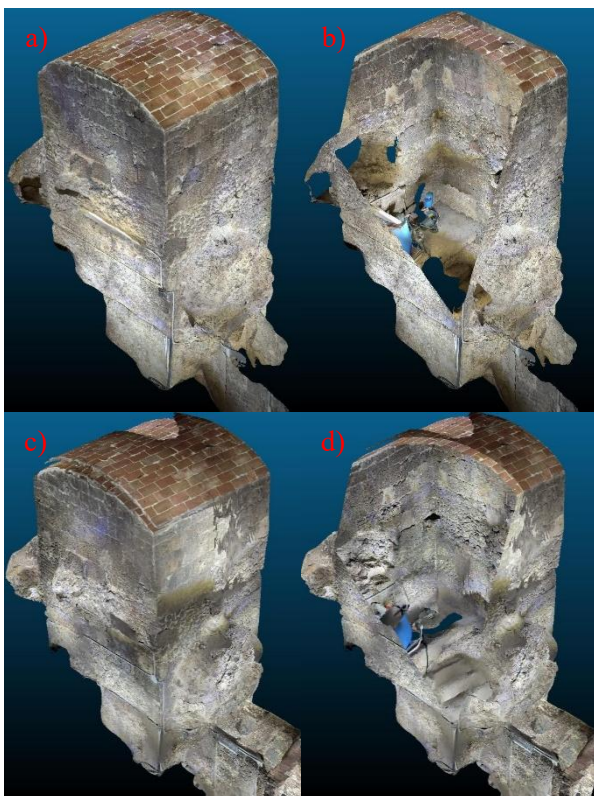
In the fourth phase, point clouds were post-processed in CloudCompare, with noise filtering, segmentation, and optimization. The 3D models were rasterized and processed to generate contour plots with 5.00 mm isohypses. Projection was unidirectional along the Z-axis; missing data were interpolated.

Elevation profiles were extracted, exported to CAD, and compared with the analogue traces.

This integration enabled the identification of topographic differences ($\approx 2.00\text{--}4.00\text{ mm}$) between real and digital surfaces, allowing classification of textures based on mortar-to-aggregate elevation differences. The roughness analysis provided insights into differing construction techniques or weathering exposure among the blocks.

4. Results

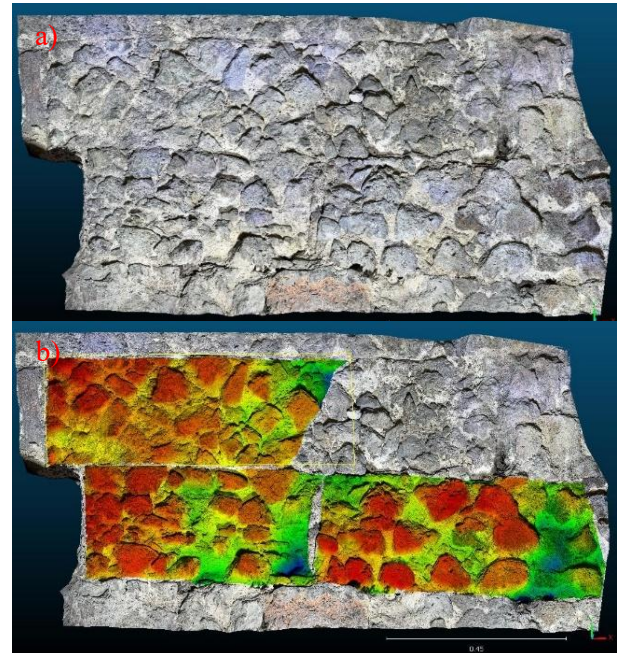
The rapid survey (Figures no. 4 a-b) provided a general representation of the internal volume of the Maconi tower and the distribution of the artificial conglomerate blocks. Acquired in approximately three minutes using the Scaniverse app (LiDAR-based, 5 mm resolution), it captured overall geometries beyond 0,50 m but lacked detail for macro-morphological variations (5-100 mm). In contrast, the detailed survey (Figures no. 4 c-d), while serving the same descriptive purpose, focused on accurately capturing wall surface irregularities. This was achieved through a slower acquisition (about ten minutes) and photogrammetric processing, again via Scaniverse, due to the size of the point cloud exceeding the app's LiDAR capacity. A total of 16 artificial conglomerate blocks were scanned at 5 mm resolution (Figure no. 5 a). Their point clouds, processed in CloudCompare, produced a high-resolution contour plot with 5,00 mm isohypses and an analytical grid for surface study (Figure no. 5 b).



Figures 4 a-b-c-d: (a-b) quick survey of the Maconi tower with section; (c-d) detailed relief of the Maconi tower with section.

Comparative analysis between topographic sections and profilometer data revealed a deviation of 2,00-4,00 mm between virtual and real evaluations. Texture analysis identified two surface types, distinguished by the elevation gap between mortar and stone

elements: one with marked differences and another with minor variations, reflection differing surface irregularity. Roughness quantification (Figures no. 6 a-b) revealed variability possibly linked to construction techniques of differential weathering.



Figures 5 a-b: Detailed acquisition of the artificial conglomerate blocks located in the internal wall facing North-East, b) analysis of the surface textures, in which it is possible to recognise a significant variation between the mortar level and the top of the elements.



Figures 6 a-b-c: contour plot of block no. 14 (a) and roughness profiles (A-A'; B-B'; C-C') (b); in green the profiles derived from digital sectioning; in red those derived from the profilometer; (c) detail circled in red of the C-C' profile.

5. Discussion of the results

The analysis of the results highlights the complementarity between the different survey phases adopted, confirming the

effectiveness of a multilevel approach for the documentation and morphological analysis of the Maconi tower.

The rapid survey, conducted in about three minutes using the iPhone Pro LiDAR technology and the Scaniverse application, produced an initial representation of the internal environment, useful for a general view of the structure. The 5 mm resolution, although limited by the distance from the walls, proved adequate to virtually restore the internal volume of the building and the arrangement of the artificial conglomerate blocks. The rapid nature of the acquisition led to a simplification of the surfaces, not allowing to capture the morphological variations between 5 and 100 mm.

On the other hand, the detailed survey made it possible to fill this gap using photogrammetry. The use of this method, although requiring a much longer acquisition time (about ten minutes), guaranteed a more accurate restitution of the wall surfaces which could translate into a greater information density thanks to the photographic data.

The processed point clouds were integrated with the analogue roughness profiles acquired using the comb profilometer. To ensure consistency between the two datasets, spatial registration was carried out using the ICP (Iterative Closest Point) algorithm implemented in CloudCompare. This allowed for a reliable geometric alignment between real and digital data, enabling a quantitative comparison aimed at evaluating the metric and morphological fidelity of the reconstructions.

The difference detected, between 2.00 and 4.00 mm, is limited compared to the scale of the analysis and is attributable both to the instrumental limits of the scanning tools, the exact positioning of the profilometer on the surface, and to the very nature of the surfaces analysed, characterized by non-homogeneous variations. The data just presented confirms the coherence between the digital twin and the physical reality of the artificial conglomerate blocks, providing a reliable representation of its topography.

The analysis of the surface texture, which allowed us to identify two different types of surfaces, allowed us to classify them based on the variation values between the level of the mortar and the top of the lithic elements.

The quantification of the roughness profile then highlighted variations that, although partly attributable to the construction methods, are above all compatible with phenomena of differentiated exposure to atmospheric agents [ABB*08]. The observed morphological heterogeneity, in fact, suggests how the selective action of exogenous agents has produced differential degradation processes over time, accentuating the irregularities of the exposed surfaces.

6. Concluding remarks

The results of the survey conducted on the Maconi tower demonstrate how the integration of different three-dimensional survey methodologies (detailed and rapid) constitute an effective approach for the documentation and morphological analysis of the artificial conglomerate blocks, allowing a complete and faithful representation of the internal volume of the building and an in-depth analysis of the conformation of the constituent materials.

The analysis of the point clouds produced as a result of the rapid survey highlighted the intrinsic limits related to spatial resolution and acquisition distance, proving effective for delineating the general volumes but inadequate for recording the morphological variations of the artificial conglomerate blocks. On the contrary, the detailed survey, based on photogrammetry and enriched by the data acquired through LiDAR, guaranteed a faithful restitution of the irregularities of the wall facings.

The integration given by the superposition of the roughness profiles acquired analogically using a comb profiler and the profiles extrapolated from the digital models obtained from point clouds, allowed a direct comparison between real and virtual dimensions, highlighting a small gap, completely contained compared to the scale of the analysis, confirming the reliability of the acquisitions and returning a metric coherence between the physical model and the digital counterpart.

This analysis method then allowed us to understand the degradation processes undergone by the conglomerate blocks placed outside and inside the tower.

Ultimately, the adopted approach proved to be replicable in similar contexts as well as effective in returning information for the morphological and material study.

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