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Augmented Reality for Knowledge Transfer of Historical Masonry Vaulting Techniques

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Abstract – New technologies and the need to preserve historical heritage are leading to renewed interest in masonry. Despite ongoing efforts in architectural and construction research, the restoration and construction of vaults and domes remain complex, presenting several challenges, including high construction costs, a shortage of skilled labour, and low productivity. Encoding highly efficient historical construction practices, such as the thin-tile vaulting technique (a scaffold-free vaulting method using thin tiles), is crucial for preserving knowledge. Generally, mastering this technique requires years of practical training under the guidance of a master mason. This paper reports the initial findings of a project aimed at evaluating how Augmented Reality can facilitate the transfer of practical knowledge. Through a case study involving the construction of a lowered vault, the impact of adopting Augmented Reality on accuracy was assessed.

I. INTRODUCTION

The European Union's economy is significantly reliant on the Architecture, Engineering, and Construction (AEC) sector, which represents approximately 6% of the European Union's gross domestic product and employs around 13.5 million individuals. However, despite significant research efforts and industrial investments, the construction sector remains characterised by limited digitalisation, a shortage of skilled labour, and fragmented knowledge. These persistent challenges underscore the urgent need for innovative construction methodologies capable of addressing and mitigating these critical issues.

Among all technologies, Augmented Reality (AR) has shown significant potential to impact the AEC sector. Augmented Reality (AR) allows georeferenced virtual information to be overlaid onto real-world environments. Existing research highlights that AR has primarily found application in the building phase, where challenges related to construction, performance, supervision, and safety have become apparent [1]. Two areas have been under investigation: technological development, i.e., improving precision devices, firmware, and robustness, and identifying AR applications during the construction phase [2].

From the technological point of view, the research focuses on improving the positioning and orientation of projections based on a classification of three methods: marker-based, markerless-based, and projection-based [3]. Technical limitations have historically favoured marker-based AR solutions; only recently has the focus shifted toward markerless alternatives [4]. The most adopted devices are smartphones or tablets, implying that AR is primarily used for learning or assessment purposes [3]. In contrast, using smart glasses like Hololens or Magic Leap introduces a transformative advantage. These devices allow hands-free operation, opening up a novel spectrum of applications [5]. From the application side, many domains are the subject of an investigation concerning the technologies adopted (marker- or markerless-based) and the device. The adoption of AR affects the entire design process by providing an easy tool for materialising information on the building site and monitoring the construction progress. As shown in research such as [6], AR can play a crucial role in the conceptualisation and design stages by defining geometrical shapes and assessing their impact within the existing context. Their relevance in the construction phase was demonstrated through several installations [7], showing potential in managing the building site. Although tests and installations have demonstrated the potential for avoiding blueprints and emphasising increased productivity and reduced waste, construction performance estimates are often based on workers' experiences or digital simulations. Only a few commercial companies [8], [9] are providing AR services for construction as a tool for management and tracing, especially for complex systems such as industrial electrical pipelines or for materialising the streets on the building site. The reasons are due to the limitations that persist, including technological issues, relatively high costs, lack of standard methodology, and ignorance [10]. Moreover, to be effective, AR requires detailed, information-enriched models, which, in practice, are not yet widely adopted; however, as mentioned above, they will soon be required under Building Information Modeling (BIM) regulations. Thus, adopting the BIM methodology facilitates the spread of AR. AR can provide valuable information to managers and builders.

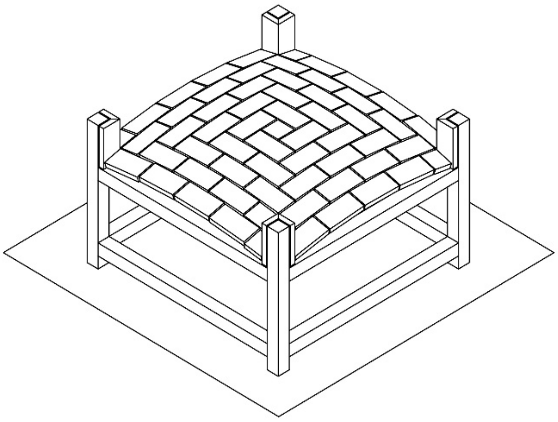

Fig. 1. The designed geometry of the lowered vault.

Through on-site projections, this technology enhances coordination [39], aids in the decision-making process, and informs builders of the material properties or presence of objects with historical significance on a construction site [40].

This investigation reports the initial findings of the Technology Application of Augmented Reality for REnovation Work (TAARReW). TAARRew aims to assess the potential impact of AR in the construction of complex masonry structures. Within TAARReW, two aspects are investigated: (1) the determination of innovative methodologies for the knowledge transfer of practical notions and (2) the evaluation of constructed works regarding construction accuracy, cost assessment, and time. This paper focuses on (2) and explicitly evaluates the accuracy achieved during the construction of scaffold-free masonry vaults relying on AR.

II. PROJECT DESCRIPTION

The TAARRew project involves a series of comparative tests to construct three lowered vaults, whose shape is illustrated in Figure 1. The vault shape is defined according to the literature on the thin-tile vaulting technique [11]. Thin-tile vaulting is a historical, scaffold-free technique that utilises gypsum-based mortar and lightweight, thin tiles. The vault, measuring 1.4 x 1.4 meters, is composed of 61 thin tiles that form the patterning shown in Figure 2. Each tile has dimensions of 3.5 x 12 x 25 centimetres and weighs 1.4 kilograms, while the mortar joints are approximately 1 centimetre. The three equal vaults were built by three different teams, one for each. For clarity, the three teams are denoted as Team 0 (T0), Team 1 (T1), and Team 2 (T2) within this paper. The members of the three teams (T0, T1, and T2) have the same practical experience but no prior knowledge of vaulting construction. Each team includes a mason and a carpenter.

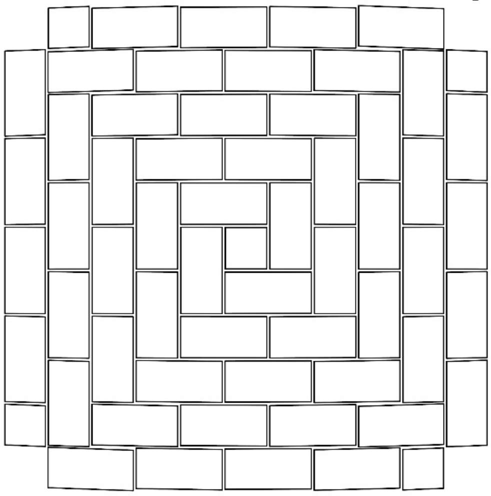

Fig. 2. Tile patterning of the lowered vaults.

Two teams, T1 and T2, were trained in the thin-tile vaulting technique, which usually requires years to master. T1 followed a traditional 2-hour training session, during which they learned the construction technique of thin-tile vaulting based on video, audio testimonies, and a few practical tests. T2 underwent the same training process as T1, along with an additional half-hour of training on AR. Within the project, AR supports the mason of T2 by projecting the information needed to learn the codified procedure of the thin-tile vaulting technique while laying operation and by tracing the correct shape of the vault. Custom algorithms were implemented to enable the sequential and automated visualisation of the various tasks. The members of T0 were not trained in vaulting techniques; however, a scaffold CNC cut was prefabricated for tracing operations and to provide temporary support to the vault.

Performance metrics, such as adherence to the designed geometry, were recorded for each team.

III. THE SURVEY

The three vaults shown in figures 3 4 and 5, built, respectively, by T0, T1 and T2 were surveyed employing a commercial Laser scanner, the Faro Cam 2 Focus 3D. For each vault, a Point Cloud (PC0, PC1, and PC2) was elaborated using Faro SCENE (www.faro.com/en/Products/Software/SCENE-Software). A test area was established, enabling the accurate overlay of all three point clouds. Thus, a set of cross-shaped markers was placed to set up the test area and to compare the structures in terms of discrepancies from the designed geometry. As illustrated in figure 3, 4 and 5, the markers serve as an external reference system to align the surveys executed on the three different shells. Another set of cross-shaped markers was placed on the three structures to improve scan alignments. Therefore, positioning one vault at a time inside the test area, four high-resolution scans were taken.

Fig. 3. Lowered vault built by T0, using the scaffold.

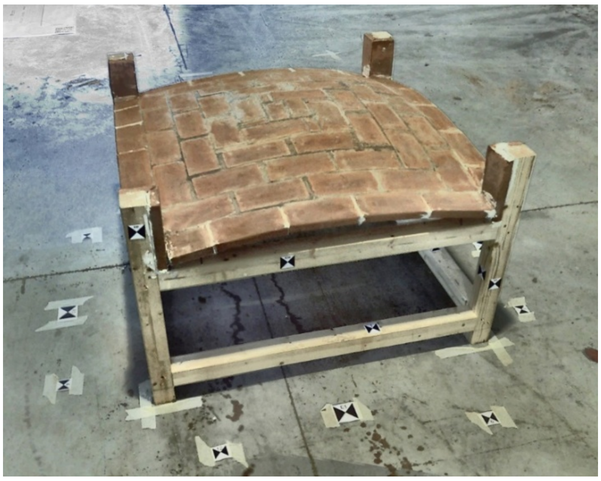

Fig. 4. Lowered vault built by T1, with the aid of a physical tracing structure.

The laser scanner parameters were selected to ensure a survey with sufficient accuracy and precision, allowing for the evaluation of geometric deviations from the designed model. The scanning was performed with a resolution of 3 millimetres at distances beyond 10 metres, a quality setting of 3X, and a reduced field of view ranging from −60° to 0° in the vertical plane and from 140° to 240° in the horizontal plane. The scan duration was reduced to 8 minutes and 34 seconds, allowing for the detection of both the RGB channel and the reflectance threshold. Back-office alignment was performed using both sets of markers, with those placed on each vault, to obtain accurate alignments. Mean errors on targets were also confirmed by evaluating scan statistics on individual points. Overall, based on approximately 48 million points surveyed, the average error was 1.4 millimetres, with a maximum of 1.7 millimetres and a minimum scan overlap of 32.6%.

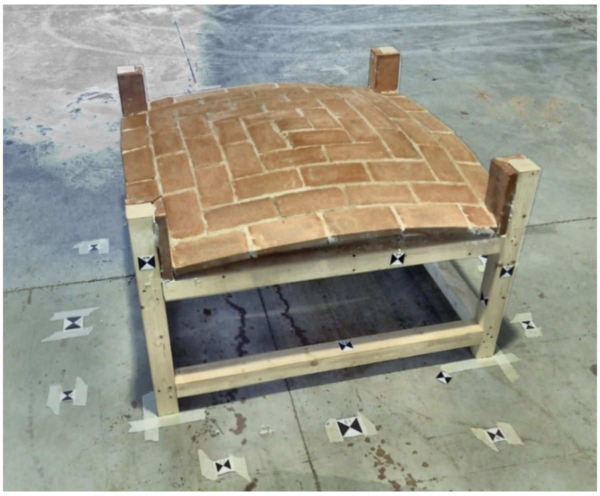

Fig. 5. Lowered vault built by T2, employing AR.

Table 1. Target errors for the three Point Cloud (PC0, PC1, PC2).

Legend		
Distance error [mm]	< 20	> 40
Horizontal error [mm]	< 20	> 40
Vertical error [mm]	< 20	> 40
Angular error [deg]	< 0.5	> 1.0

Target Errors	**PC0**	**PC1**	**PC2**	**Total**
Iterations Dist. Error [mm]	7.8	5.0	3.0	18.7
Average Distance error [mm]	4.0	2.5	2.1	4.2
Iterations Horizontal error [mm]	7.7	4.9	2.9	17.2
Mean Horizontal error [mm]	3.8	2.2	1.9	3.9
Iterations Vertical error [mm]	2.8	1.6	1.6	12.4
Mean vertical error [mm]	0.9	0.9	0.8	1.1

According to these error distributions, PC0, PC1, and PC2 provide a valuable source for estimating the displacements and deformations that occurred during the construction of the three vaults.

The comparison of PC0, PC1, PC2, and the designed geometry was executed using the free and open-source software Cloud Compare (CC) (www.danielgm.net/cc/) [12]. CC software provides dedicated tools for point cloud analysis, enabling the determination of geometrical quantities. Using the designed geometry defined for T2, the point clouds of the three constructed vaults (PC0, PC1, PC2) were imported into CC and overlaid on the designed model, aided by markers placed in the test area.

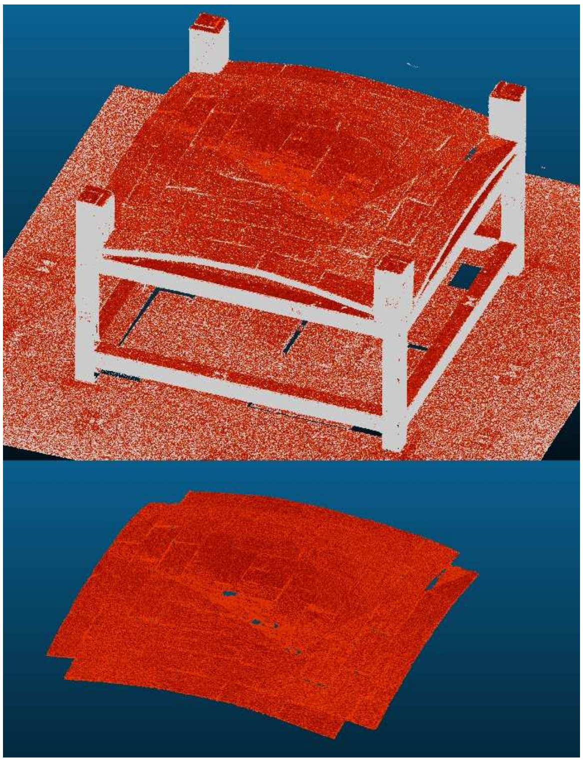

Fig. 6. PC0 of lowered vault built by T0. At the top, PC0 before the methodological cleaning process. At the bottom, PC0, after the segmentation process.

The purpose of this process is to compare the extrados surface of the vault with that of the designed geometry and quantitatively evaluate the differences generated by the construction methods. For this purpose, a uniform and automated methodology was identified to correctly segment the different point clouds, isolating only the upper face of the thin tiles.

The first step is to identify the normals of the point cloud. This method attempts to consistently reorient all the normals of a cloud. The algorithm initialises from an arbitrarily chosen seed point and propagates the orientation of the normals from one nearby point to another. The propagation is performed using a Minimum Spanning Tree algorithm [13] (parameters: local surface type - PLANE; Octree radius - 10; Minimum Spanning Tree - Knn). By filtering the resulting normals according to the inclination angle from the versor *z* and within a range of [0°-30°], the points that belong to the vertical faces of the vaults were excluded. Then, by exploiting an automatic segmentation algorithm that can cluster isolated point sets (Label Connected Component on en.wikipedia.org/wiki/Connected-component_labeling), the points that are not part of the vault are removed. Indeed, the algorithm subdivides the clouds into smaller clouds, separating them with a criterion of minimum distance (parameters: Octree level - 10; Minimum points per component - 10).

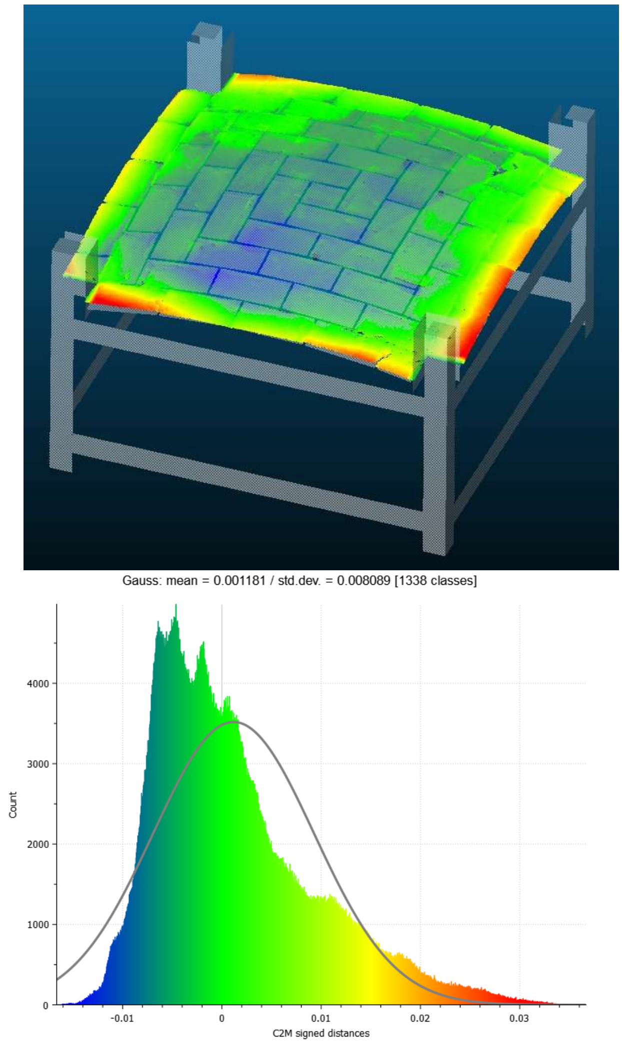

Fig. 7. Comparison of PC0 vs. designed geometry. At the top: geometrical discrepancy colour map. At the bottom: distribution of geometrical discrepancies

The developed methodology automatically removes all points detected that belong to the wooden frame and the floor, which are not relevant for evaluating geometrical discrepancy.

IV. RESULTS

The three comparisons between the point clouds and the designed geometry reveal the geometrical discrepancies. Indeed, the geometrical discrepancy colour map shown in Figures 7, 8, and 9 display a blue homogeneous area for PC0, as seen in Figure 7, which corresponds to the points positioned below the designed geometry. At the same time, PC1 and PC2 display more irregular maps, particularly PC1, where depressions are shown in blue and peaks in red (see Figures 8 and 9). Geometrical discrepancy ranges from -1.8 cm to +3.4 centimetres for PC0, -1.4 to +2.6 centimetres for PC1, and -1.4 to +3.0 centimetres for PC2.

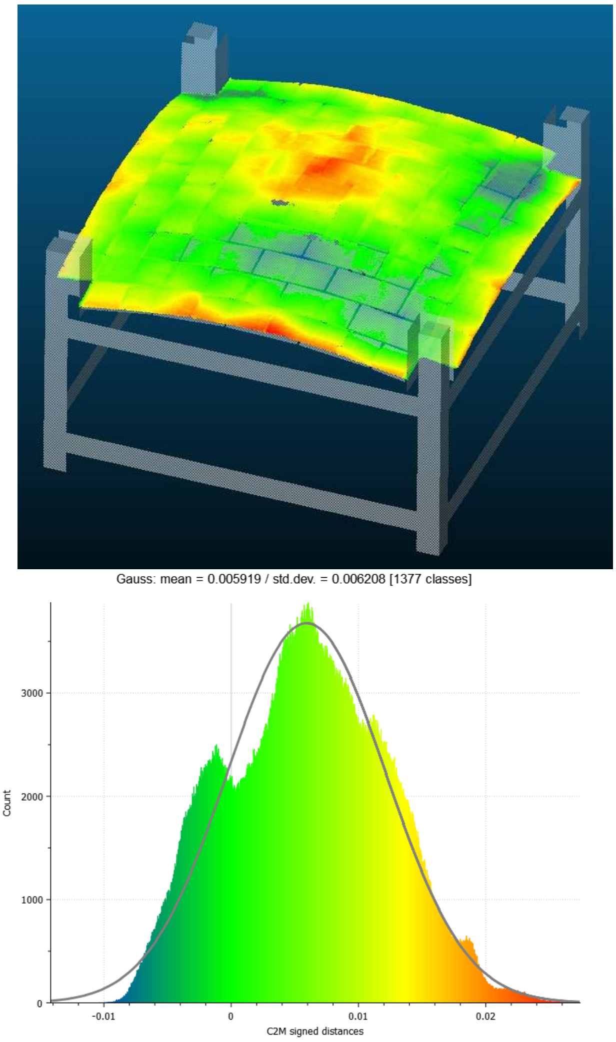

Fig. 8. Comparison of PC1 vs. the designed geometry. At the top: geometrical discrepancy colour map. At the bottom: distribution of geometrical discrepancies.

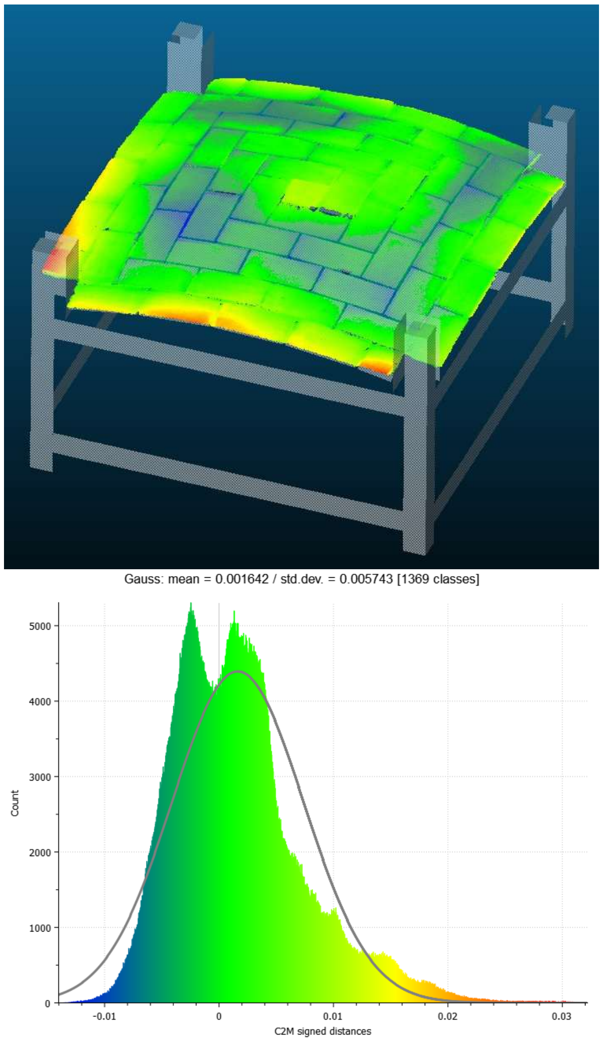

Fig. 9. Comparison of PC2 vs. designed geometry. At the top: geometrical discrepancy colour map. At the bottom: distribution of geometrical discrepancies.

Positive values in the range indicate that the measured points lie above the designed geometry, whereas negative values correspond to points positioned below it. The maximum geometric discrepancies relative to the design are 2.42% for PC0, 1.86% for PC1, and 2.14% for PC2. These low percentage values suggest a high degree of conformity with the intended design. The Mean Discrepancy (MD) and the Standard Deviation (SD) evaluated using standard distribution are approximately MD = 0.11 centimetres, SD = 0.008 for PC0, MD = 0.59 centimetres, SD = 0.006 for PC1, and MD = 0.16 centimetres, SD = 0.005 centimetres for PC2. The values suggest that the mean discrepancy between PC0 and PC2 is comparable, while PC1 displays a MD three times larger than PC2.

V. DISCUSSION

The geometrical comparison revealed minimal differences among the three vaults built by the three teams, with an overall average error of less than 2.5% in all cases. The data show that the adoption of AR led T2 to achieve greater accuracy than T1, similar to T0 (which adopted physical supporting structures). Although the difference between PC1 and PC2 is approximately 4.3 millimetres, this variation is significant when considering the small scale of the structure, highlighting the measurable impact of Augmented Reality.

The vault built by T1 exhibits a more regular distribution of geometrical discrepancy than the one computed for T2, illustrating the significant impact of AR. Thus, it is possible to assume that the distribution of geometrical discrepancies could be affected by drifting. This behaviour could explain the unconventional geometrical discrepancy distribution of PC2, which shows a double peak centred in proximity to 0.0 centimetres. Indeed, both T1 and T2 are characterised by a distribution similar to a Gaussian curve. A key finding is represented by the discrepancy colour maps shown in Figures 7, 8, and 9, where PC1 exhibits an instant variation from blue to red, suggesting the existence of a concavity and highlighting the challenge of mastering the thin-tile vaulting technique. Further study will investigate more accurate geometrical analysis.

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