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RESEARCH

The Illusory Architecture of the Camera di Giove in Sassuolo

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Abstract
The prospective illusionism of vaulted systems is a research field in which the study of geometry, survey, and architectural representation converge. The painting defines a precise scale and orientation relationship with the observer, while the morphology of the vaulted system increases the architecture's spatiality. Therefore, the study of quadrature framed in vaulted surfaces implies investigating systems based on stratifications of real and ephemeral information. The present research examines the Camera di Giove, a vaulted room located in the Ducal Palace of Sassuolo, an important residence of the Este family. The chamber represents a typical Baroque example of an extension of spatial perception, thanks to the relationship with the nearby rooms and the vertical perspective of the vaulted painting. The research suggests a path of analysis that highlights the geometric–mathematical relationships existing between the quadrature, the vault, and the architectural space.

Keywords Perspective · Ducal Palace of Sassuolo · Camera di Giove · Survey of vaulted systems · Virtual reality

Introduction

The form of expression known as "quadrature" was aimed at constructing perspective illusions that establish a relationship with the observer according to a certain scale and orientation. Quadratura, which reached the apex of realization in the Baroque era, can increase the perception of spatial dimension by means of projections of architectural drawings onto flat or curved surfaces, creating a harmonization of

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the real and illusory space. The morphology of the surface projection assumes a critical role in this process of spatial expansion. For example, vaults can provide the architecture with a more accentuated and vertical spatiality, amplifying the illusion from a perceptual point of view. So, the study of the vaults with quadratura is based on the stratification of real and ephemeral information. While morphological and compositive studies make it possible to identify the relationship between quadrature and architecture, the analysis of the painting in perspective sheds light on the relationship between the painted image, the vaulted surface, and the architecture.

This research focuses on the Camera di Giove, a vaulted room located on the main floor of the Ducal Palace of Sassuolo, an important residence of the Este family during the Baroque period. The presence of various quadrature in the palace defines a sequence of illusory spaces in a scenic environment, reinforced by a strong architectonic perspective. The Camera di Giove represents an admirable example, due to the spatial relationship with both the nearby rooms and the above space of the illusionistic ceiling painting, which gives a strong impression that the space is actually much higher than it really is. In the article we suggest a path of analysis aimed at understanding and highlighting the geometric-mathematical relationships between the quadrature, the vault, and the architectural space.

Historical Background

The Ducal Palace

The Ducal Palace of Sassuolo is one of the most important Baroque residences in northern Italy. Its origins date back to the time of Matilde di Canossa. In 1373, the palace became an Este's property under Borso d'Este, who promoted the first works to convert the fortified manor into a court residence (Braidi and Monti 2007). After changing hands during some historical events, the building came back into the Este's possession under Francesco I during the sixteenth century. In 1634, he commissioned the architect Bartolomeo Avanzini and the hydraulic engineer Gaspare Vigarani to convert the ancient family building into a modern extra-urban residence (Fig. 1). Francesco I also involved a team of artists to perform an architectural and decorative reinterpretation of the rooms, turning this building into an admirable work in which perspective and architecture define refined spaces. The palace's decline began with the Napoleonic requisition, and it passed through several owners before becoming public property in 1941, hosting the historic military academy of Modena. After many years of military administration and complex restoration work in the 1980s, management of the palace was entrusted to the Italian Ministry of Cultural Heritage and Activities in 2004. Still today, the presence of fountains, sculptures, wall paintings, and stucco decorations convey the sense of historical importance of the palace.

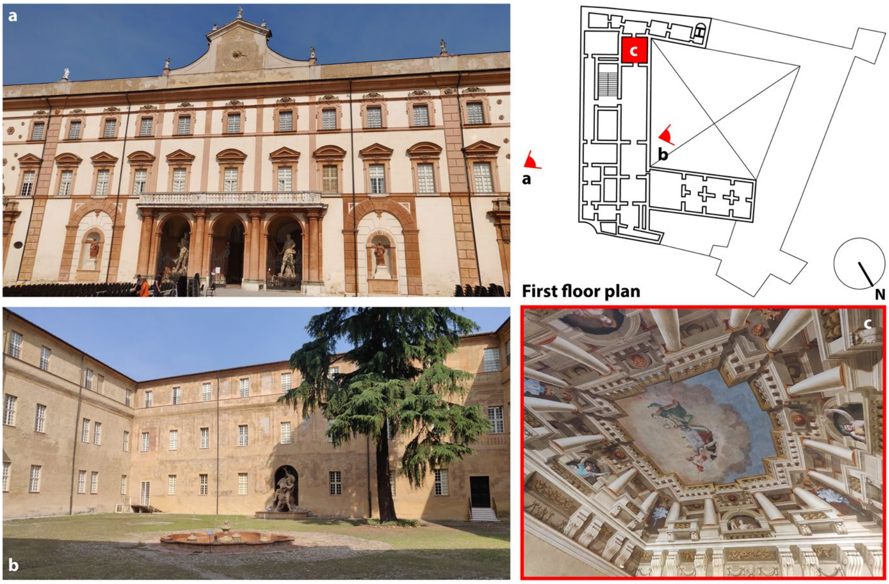

Fig. 1 **a** The main palace façade; **b** the inner courtyard; **c** plan locating the Camera di Giove; the vault of the Camera di Giove

Camera di Giove

The Camera di Giove is a room on the main floor of the palace, defined by a vault system with a dizzying perspective foreshortening, painted by Ottavio Viviani (1579–post-1646). The figurative apparatus was carried out by Jean Boulanger, a visionary court painter. In the vault's center, the figures of Jupiter (Giove, for whom the room is named) and Juno banqueting served by Hebe suggests a possible use of the space as a dining room. Leaning out from the false balconies are four divinities who preside over the banquet's success: Bacchus, the god of wine; Flora, the deity of flowers; Ceres, goddess of wheat crops and then bread; and Pomona, mythical protector of "pomari" or fruit gardens.

In the corners are the coats of arms of the House of Este, the white eagle on a blue field. This vault testifies to the Baroque desire to go beyond the physical space. The perimeter walls, probably painted, were plastered in the seventeenth century. Precise attribution of the artistic work to either Viviani or Boulanger, beyond the figurative apparatus, is complex, because no preparatory drawings have been found. Thus the quadratura analysis in this present study did not consider this distinction, focusing on the architectural drawing. The painter Ottavio Viviani worked with Tommaso Sandrino, a famous painter coming from Brescia School (Pontoglio Emilii 2016), whose works show the technique and stylistic features present in Viviani's quadrature. Viviani worked mainly in his territory, i.e., the church of San Giorgio (Bagolino), the church of Saints Faustino and Giovita (Brescia), and the church of Santa Maria in Valvendra (Lovere), devoting his figurative art mainly to quadrature.

Space Measurement and Analysis

Geometrical Acquisition

The application of different surveying methods allows us to reach the geometric knowledge of an architectural environment. In the last two decades, technological and scientific developments have consolidated procedures and results in active and passive 3D survey techniques. The introduction of 3D laser scanners for the Cultural Heritage survey has enormously changed the spatial knowledge of artifacts and the level of analysis achievable (Apollonio et al. 2013), acquiring multi-resolution information for the reconstruction of reality-based models (Guidi et al. 2014). At the same time, photogrammetric methodologies have also undergone a strong development (Rodríguez-Navarro 2012), thanks to the introduction of several image-based software and algorithms for automatic image matching (Remondino and El-Hakim 2006), reaching results comparable to range-based methodologies (Luhmann et al. 2013). The massive use of SfM approaches has led to consolidating the use of ortho-images as a metric tool for geometric analysis (Chiabrando et al. 2014). Finally, there are some published works devoted to suggesting ideal methodologies for surveying curved surfaces (Mancini et al. 2014) or focused on the general difficulties encountered in surveys of vaulted systems (Bianchini 2010), while other studies refer to vault stereotomy (Calvo-López and Alonso-Rodríguez 2010), constructive and structural analysis (Lerma et al. 2005), and digital modeling (Compán et al. 2015). Both active and passive survey methodologies have been applied in the 3D data acquisition campaign of the Camera di Giove.

The survey of the architectural space was carried out by a phase-shift 3D laser scanner Focus X120 (Faro), acquiring a dense cloud of colored points with an average surface resolution of 1.5 mm and a data accuracy of 0.4 mm (Fig. 3). The introduction of two lower-resolution additional scans at the two main accesses allowed the reduction of the shadow areas, recording the geometric information useful in the virtual modeling step (Fig. 2). The single point clouds were oriented

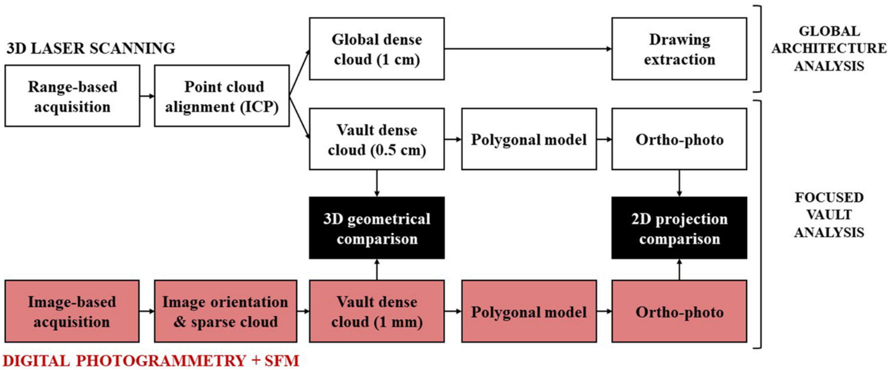

Fig. 2 Comparison between the two survey methodologies and data verification respect to the analysis purposes

using homologous point recognition (ICP), merging into a single cloud that was resampled with a 0.5–1 cm sampling step (Table 1). This range-based data was used in this research as a gold standard. Then, a photogrammetric survey of the vault was planned to obtain a higher density of the geometric data and a better quality of the radiometric data. A D5200 (Nikon) camera with AF-S DX 18-55 lens (Nikkor) and 23.5×15.6 mm (6000×4000 pixels, 24 Mpixel, 1.5 crop factor) CMOS sensor was applied in two different campaigns: the first one based on a nadiral camera axis relative to the springer plane, and the second one using a camera with the oblique axis, aimed at capturing the entire edge portion of the vault (Fig. 3). A ground control points (GCP) survey was not planned, due to the vault's limited dimensions, the chromatic surface characterization, and the three-dimensionality of the vault shape. For this, a photogrammetric data validation phase was considered. The first photogrammetric block consists of 27 images with an average acquisition distance of 5 m and a GSD on the vault of 1.1 mm, foreseeing an overlap of 60–80% between every single stripe and a baseline of one-third of the acquisition distance. The second block consists of 12 images, with a similar average distance but a variable GSD. Both image blocks were captured by the same camera set-up mounted on a tripod: 18 mm focal length (27 mm equivalent focal length), focal aperture angle of 66 deg, ISO 800, 1/2 s exposure, f/8. All images were processed inside Metashape (Agisoft) software, orienting every single frame and defining a sparse cloud and dense point cloud. Both range-based and image-based point clouds were used to generate polygonal models, which were projected on the vault springer plane, obtaining two ortho-images with a close to millimeter resolution (Fig. 2 and Table 1).

Architecture Analysis

The study of architecture requires an overall knowledge of the building. In the present case study, the investigation focused on the visible elements, analyzing the vault system in depth. Relative to this latter, some researches have defined the nomenclature, typology, and geometric construction of the vaults (Migliari and Fallavolita 2009), while others have suggested the analysis of the entire vault families (Huerta 2007), arriving at their shape idealization (Spallone and Vitali 2017). Starting from this theoretic framework, we used the range-based point cloud as a reference to draw orthogonal views of the room, exploiting the great data precision and the chromatic information (Fig. 4). An architectural analysis of the modular recurrences has been carried on, referring to the historic measurement units of

Table 1 Summary of the main parameters of survey and data processing

Survey technique	# Scan/image	Mean Res. (mm)	# Points (10^6)	# Polygon (10^6)	Ortho-image (mm/pix)
Range-based	3	1.4	200 (architecture); 36 (vault)	28.9 (vault)	1.1
Image-based	39	1.1	39	25	0.72

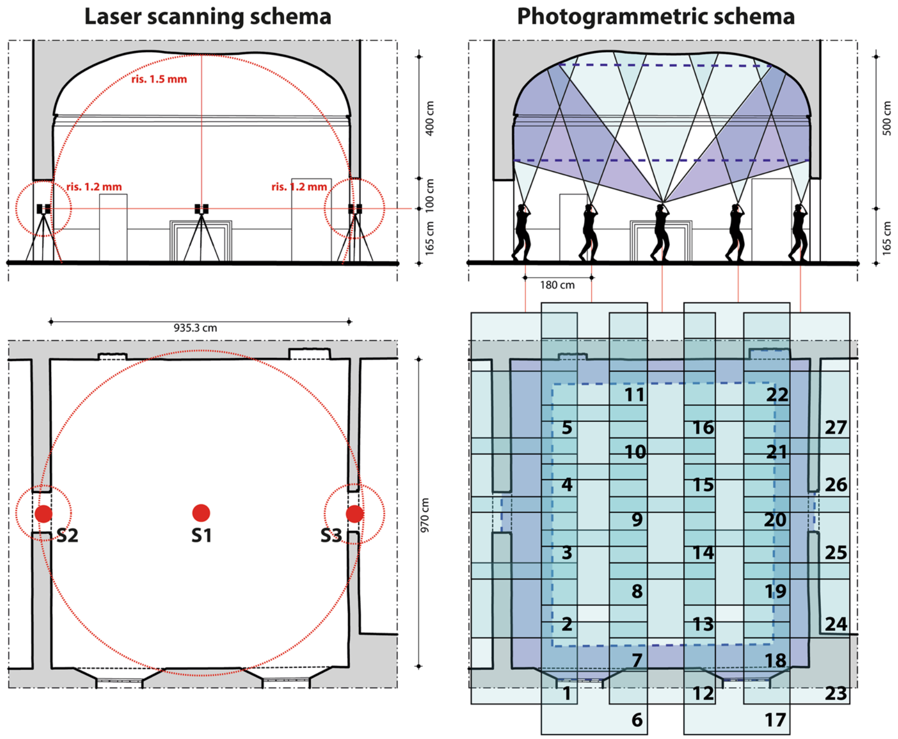

Fig. 3 Two surveying methodologies schema in plan and section: on the left the range-based approach with scan stations, average resolution, and instrumental height. On the right, the two photographic campaigns with nadiral axis (light blue area) and oblique one (blue and dotted area)

Modena territory, looking for the original compositional scheme. Correspondences with the Modenese foot (0.523048 mt), a submultiple of the pole (=6 feet) were found, showing in plan a ratio of about 18×19 feet, corresponding to 3 poles for A-C sides and 3 poles plus 1 foot for B-D sides (Fig. 5). A ratio of 3×2 poles was also confirmed in height, so the unit relation also corresponds in the vertical direction. Considering the deformation of the vault, we can assume that the original height was 13 feet, providing essential information for the hypothetical reconstruction of the original vault shape. Polycentric curves have approximated the AA' and BB' sections with three centers, which define the generators of a rectangular pavilion vault (Fig. 5). The radii of the polycentric curve are quite close to precise local unit measurements, even if the construction hypothesis leaves a margin of uncertainty on the original shape.

From the morphological point of view, the room walls present some deformations, especially along the external wall with the windows. As far as the vault is concerned, the geometrical distortions are highlighted both by an altimetric analysis and by a sequence of 5 cm contour lines (Fig. 6). Both representations highlight a structural behavior in which two sides of the vault, along the B–D sides, present a constant

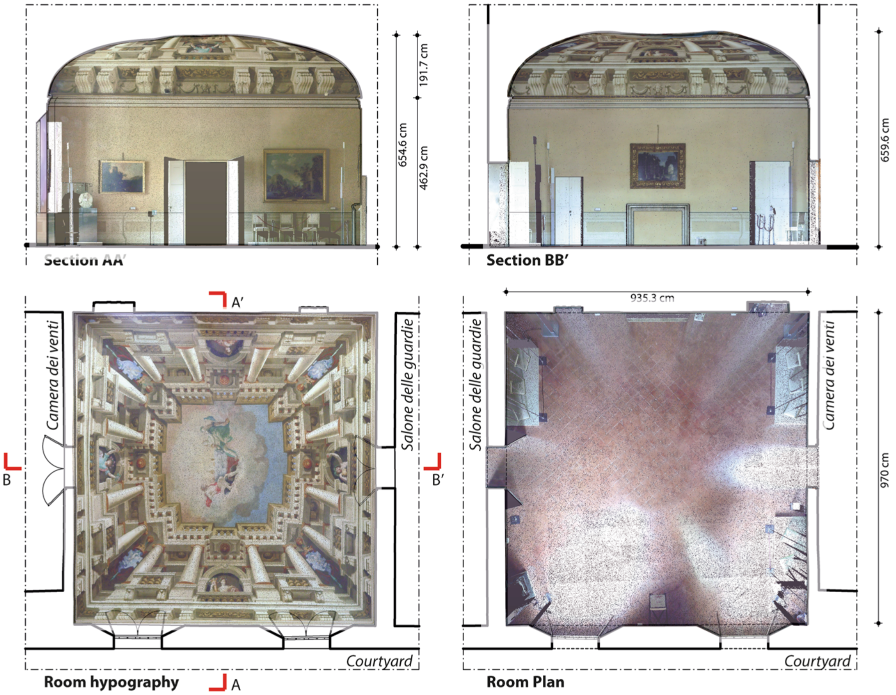

Fig. 4 Orthogonal views of the room with the superimposition of the colour point cloud

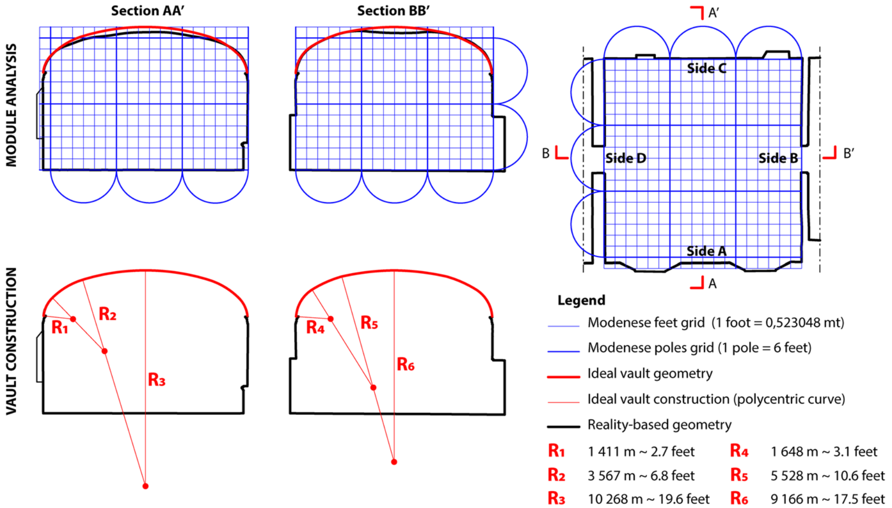

Fig. 5 Modular analysis of the room and geometric analysis of the vault curvature

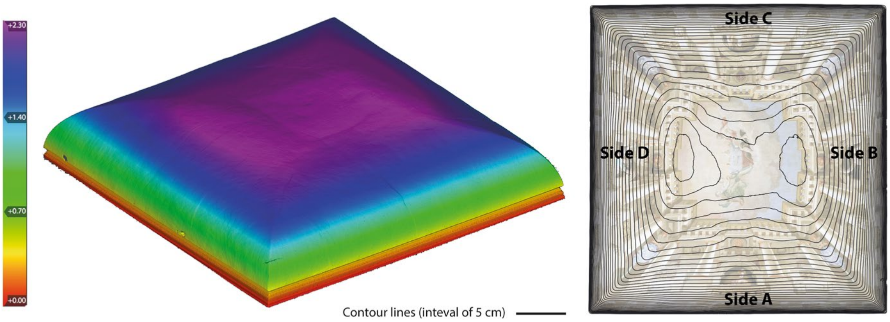

Fig. 6 On the left, height colour map of the vault concerning the springer plane, on the right, the contour lines map superimposed the ortho-image

deformation given by a lowering of the whole vault. On the other hand, along the A–C sides, the vault shows two localized failures close to the ridge.

Vault Data Analysis and Validation

The photogrammetric results present a higher quality in terms of data density and color description relative to that coming from 3D laser scanning (Fig. 7). It has been necessary to provide their validation in terms of geometric quality, planning a double comparison between range-based and image-based data, in order to verify their reliability for geometric analysis.

Regarding the first verification, the scaled photogrammetric point cloud was oriented and superimposed on the range-based point cloud, highlighting a millimetric deviation and a substantially symmetrical color distribution as a result of a good alignment between the two-point clouds (Fig. 8). The map shows some

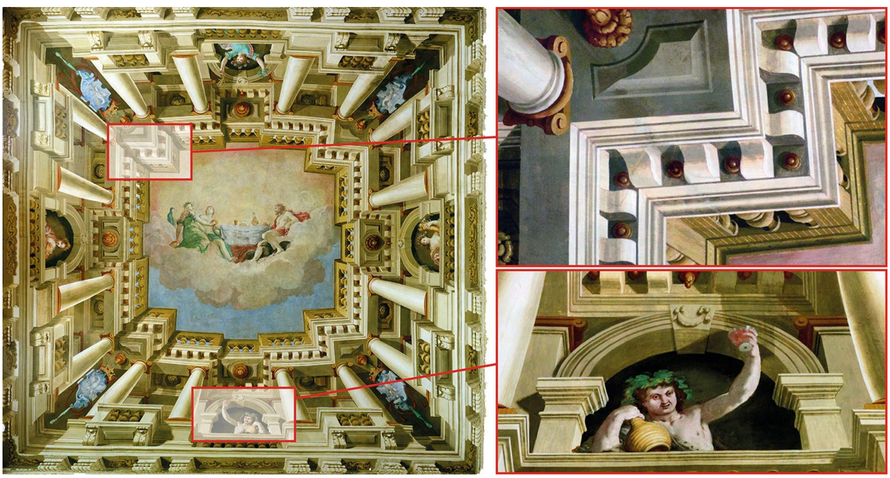

Fig. 7 Ortho-photogrammetric image and two details of the vault painting

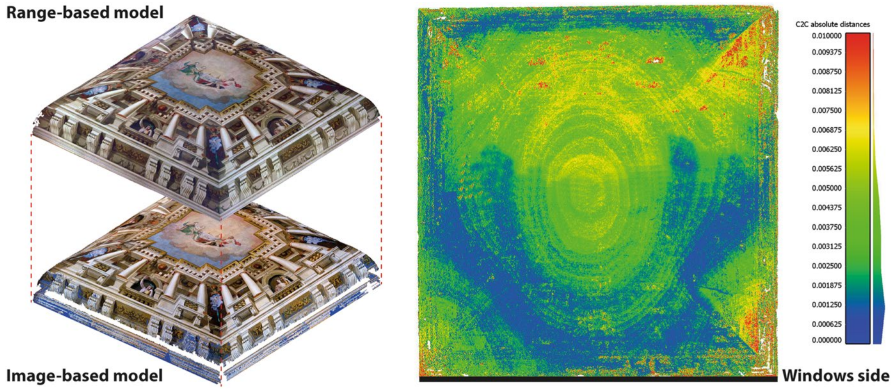

Fig. 8 Comparison schema between the two-point clouds and colour map with distance variation

asymmetries, which could be the result of a wrong 3D acquisition for the effect of the stronger natural lighting in some areas. These have produced a slightly noisier data with the same parameters, increasing the deviation between the two-point clouds.

Once the morphological coherence between the two clouds was demonstrated, a second validation based on the comparison between the two ortho-images was planned. The purpose of this verification was to highlight the introduction of possible geometrical distortion parallel to the springer plane, which can lead to a misunderstanding in the prospective analysis of the quadratura (Fig. 9). From the methodological point of view, the orthophoto generated on the springer plane by

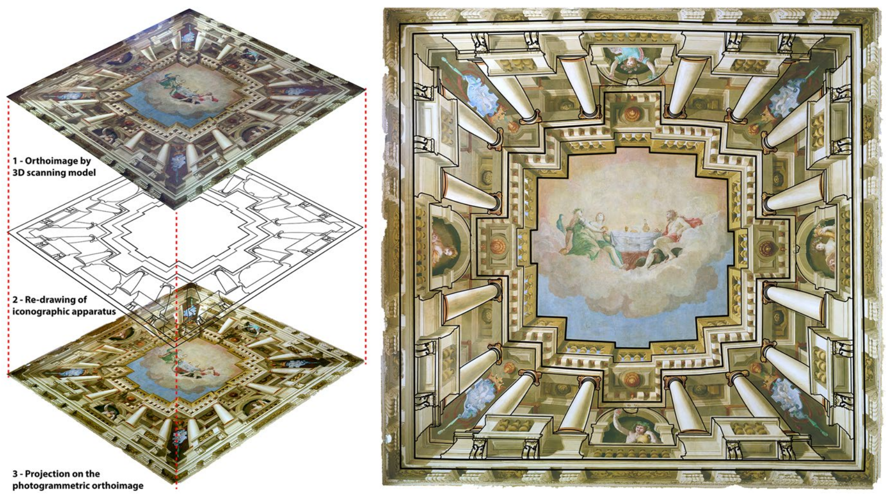

Fig. 9 On the left, schema of the manual extraction process of the features with respect to the ortho-photos; to the right overlap between the drawing and the photogrammetric ortho-image

the range-based polygonal model was used to redraw the main geometries of the quadratura.

In a second phase, these were superimposed on the orthophoto created on the same plane by the image-based data, verifying the deviations between lines and images. The result (Fig. 9) shows a substantial coincidence between these two elements, with small variations in peripheral areas. Also, the comparison shows that the Z variation does not affect the geometric XY distribution of the quadrature. Finally, the analysis highlights two portions of the vault subject to a localized geometric deformation, which leads to a distortion of the lines of the prospective painting. For this reason, the geometric analysis was planned on one of the two portions with a uniform deformation. At the end of this validation step, the use of the photogrammetric orthophoto for the perspective analysis can be validated.

Geometric Analysis

Because the body of literature about the state of the art of illusory paintings on vaulted systems is vast, the examination of it has been restricted to Italy, in the search for some thematic cues for defining a cognitive framework and support the discussion. Starting from some of the historical treatises (Piero della Francesca 1482; Barozzi da Vignola and Danti 1583; Alberti 1651; Pozzo 1693), the first recent works date back to the 1970s, through the analysis of some painted architectures by Mantegna (Fasolo 1965) and Giorgio Vasari (Fasolo 1969). Following these studies, in 1984, Orseolo Fasolo suggested a classification between a 1st-degree perspective, aimed at representing architecture scenes bound in the physical surface, and the 2nd-degree perspective, in which the representation comes out of the surface walls or ceiling, merging with the real space into a single illusory architecture (Fasolo 1992). However, it was only at the end of the twentieth century that the first extensive study on the field of quadrature appeared, mainly located in the areas of Rome and Lazio (Migliari 1999). The results obtained in this research defined the basis for future studies of architectural perspectives related to the Baroque period (Farneti and Lenzi 2006) or to a longer historical period in Italy more generally. In addition, other analyses have been carried out on the connection between illusory art, perception, and architectural perspective (Mancini 2015), on the relationship between perspective and stereotomy (Calvo-López and Alonso-Rodríguez 2010), on the relationship between drawing and the vaulted systems (De Rosa 2016), on the construction of particular perspective paths (Farroni 2019), and on the relationship between paintings, lights, and shadows.

The Painted Architecture

The quadratura framed in the vault of the Camera di Giove is a 2nd-degree perspective illusion, showing an imaginary architecture in perfect harmony with the real architecture. The shadows in the painting, created according to the real light sources, as well as the real size of the architectural and figurative elements painted, emphasizes the continuity between illusory space and the real one. The analysis didn't consider figurative and light components, although the shadows contributed to understanding the illusory space. Viviani's illusory architecture is characterized by a four-fold symmetry such that, if detached from its architectural context, only the figurative apparatus indicates orientation. A series of architectural elements define the architectural space, in which columns and parapets provide a greater visual impact. All the other secondary elements contribute to the spatial configuration. In each vault quadrant corresponding to one room side, there is the painting of four slender Ionic columns resting on a high molded pedestal. The two central columns frame a parapet with bottle-shaped balustrades slightly behind the outer edge of the pedestal of the columns, from which one of the four gods protrude, while a round arch supported on square pillars is in the background. The arch, together with the pilasters in correspondence of the columns, belongs to a recessed plane. Also, the two columns to the right and left of the central columns hold another balustraded parapet that rests on a pair of elements decorated with acanthus leaves, defining a space covered by an articulated coffered ceiling. Towards the top, Viviani's perspective illusion is crowned by an imposing balustraded loggia that stands out towards a sky partly covered by clouds.

The Perspective Restitution

Given the symmetrical composition, the portion of the vault set on the side A (Fig. 5) presents a uniform deformation. For this, it has been chosen for the restitution. In this area, the painted lines supposed to be parallel to the geometric picture plane preserve their condition of being parallel. Due to the lack of preparatory drawings and evidence about the ideal point of view, a simplification was effected using the ortho-image for the perspective restitution process.

The main point O_0 was defined as assuming the geometric picture plane coincident with the springer one, by extending the straight lines orthogonal to the painting, and subsequently, the horizon line passes through O_0. This first step has confirmed that the perspective is monocentric. Since no dimensional indication of the painted architecture is available, the ground line was assumed to coincide with the lower limit of the fresco. It was necessary to determine the observer's main distance and, therefore, the circle of distance and O*, to complete the perspective reference system.

A round arch, characterized by a geometric construction that lies on parallel plane respect to the springer one has been identified. It is in the center of the illusory architecture and inscribed in a semi-square. Considering the entire square and extending its diagonals, it has been possible to define on the horizon the vanishing points of the straight lines inclined at 45°, which correspond to the intersection between the circle of distance and the horizon line. The point O*, which overturns the point of view on the picture plane, was then defined, representing both the distance of the ideal observer and the homology center. The principle of homological correspondence has been used to identify a geometrical relationship between the entire painted illusory architecture and its representation. Once the perspective reference was identified, it was possible to represent the square, and consequently, the arch in true form. The corresponding vertices points of the two squares, the one represented in true form and the one in perspective belonging to the geometric plane, are perfectly aligned with the homology center O*, validating the procedure adopted (Fig. 10a).

The obtained reference system allows the main distance to be determined, corresponding to about 5.70 m. Therefore, the ideal observer does not correspond to the real one, whose distance from the fresco is at less than 3 m. Therefore, the ideal observer is placed outside the physical space of the room (Fig. 10b).

The procedure based on homologous correspondences was reiterated to extract the principal elements painted in the vault portion, obtaining plan, elevation, and profile of the illusory architecture in true shape (Fig. 11). The result, compared with the modular grid already used, highlights the correspondence with the Modenese unit used in the real architecture for the space of the painted architecture: the side galleries are 2 feet wide, while the height is about 3 poles and 5 feet.

Features of the Reconstructed Illusory Architecture

The reconstructed illusory architecture, defined by a highly articulated two-level gallery, makes the perceived height of the space almost double that of the actual space. The columns are oval in section, and the pedestals, on which rest the outermost columns, present a reduced size compared to the central columns, while the section of the columns remains unchanged. There are two elements that break the rules of perspective: the upper balustrade, which stands out

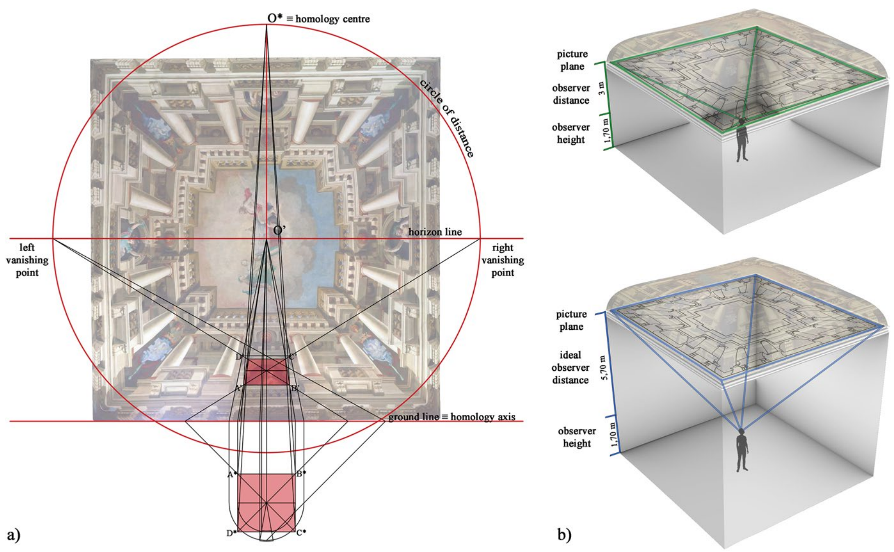

Fig. 10 **a** The construction of the geometric reference system; **b** schema of the position of the real and ideal observer

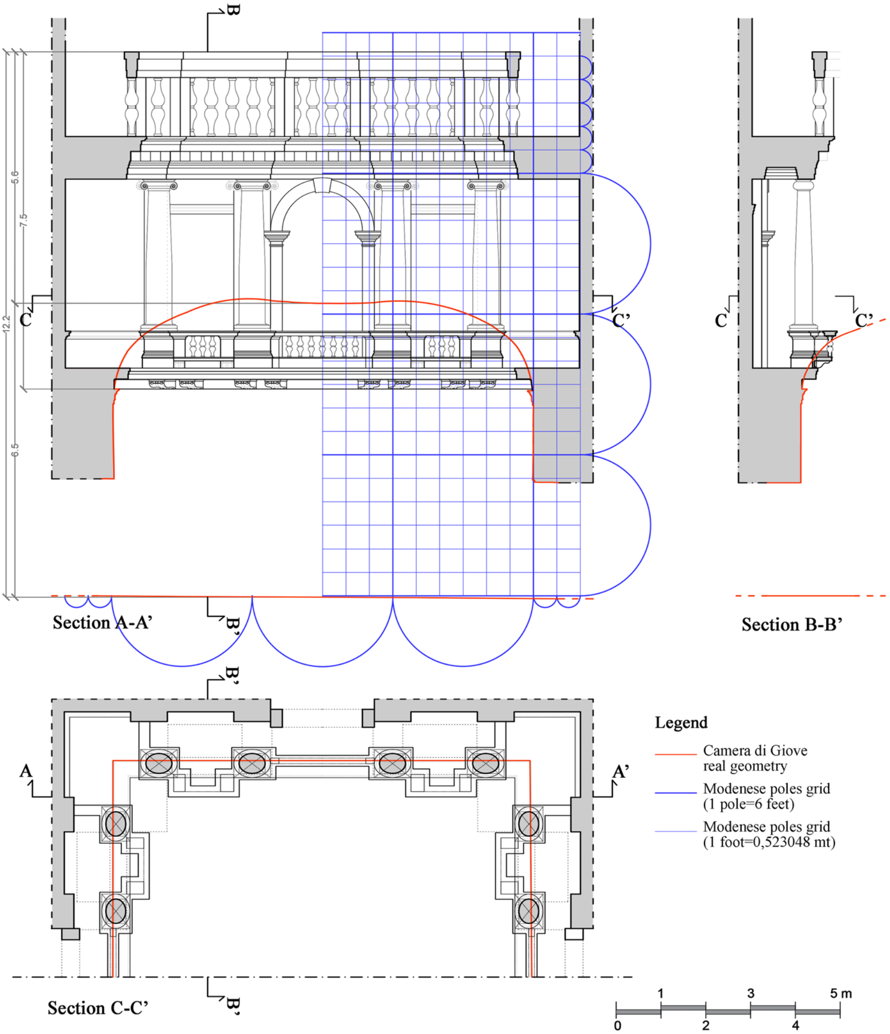

Fig. 11 The result of the perspective restitution: elevation, plan, and section of the illusory architecture compared with the modular grid

against the natural element of the sky, is significantly higher than the parapet below (see Fig. 15a), while the columns supporting the balustrade do not show any horizontal squashing, a normal consequence of the perspective effect. These exceptions to the rules of perspective, also used in accelerated solid perspectives, offer the possibility of modifying the perception of the painted space, which thus appears much higher.

Virtual Architecture

In the study of cultural heritage, the construction of 3D models mainly involves the exploitation of analysis, interaction, and simulation capabilities of digital artifacts in a virtual environment. In many cases, the reality-based polygonal model is translated into a parametric one, following an interpretation and simplification process to achieve better geometric control of the reconstructive model. The virtual reconstruction of the Camera di Giove has been planned on both the adherent and interpretative approaches. The first methodology, devoted to the Camera di Giove reconstruction, has used a sequence of sections extracted from the range-based point cloud, from which different parametric surfaces of the walls, the vault, and the openings have been created. In this phase, different modeling approaches of the vault have been tested, comparing the undeformed 3D model and the one adapted to reality with the range-based model. This analysis showed a deviation of 30 cm in correspondence with the former vault deflections, and a centimetric deviation for the latter, which was used in the virtual model (Fig. 12). Once the virtual Camera di Giove had been completed by inserting the secondary architectural elements, the creation of the adjacent rooms was started, simplifying the range-based data and the direct survey measurements acquired in situ. The opportunity to interact with the complete 3D model, managing vertical or horizontal sections and virtual viewpoints, allowed the analysis of the perspective interactions between the different rooms.

The results highlight the presence of an optical cone crossing all the rooms, demonstrating the attention to the scenic effects in the palace architecture (Fig. 13).

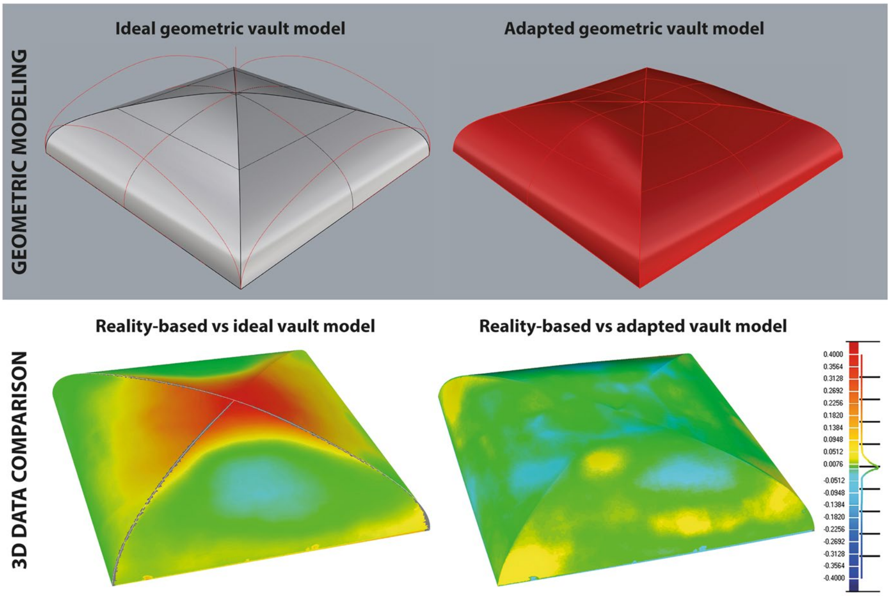

Fig. 12 Geometric comparison between the ideal parametric model of the vault and the one adapted to the real data, with relative deviation analysis respect to the range-based model

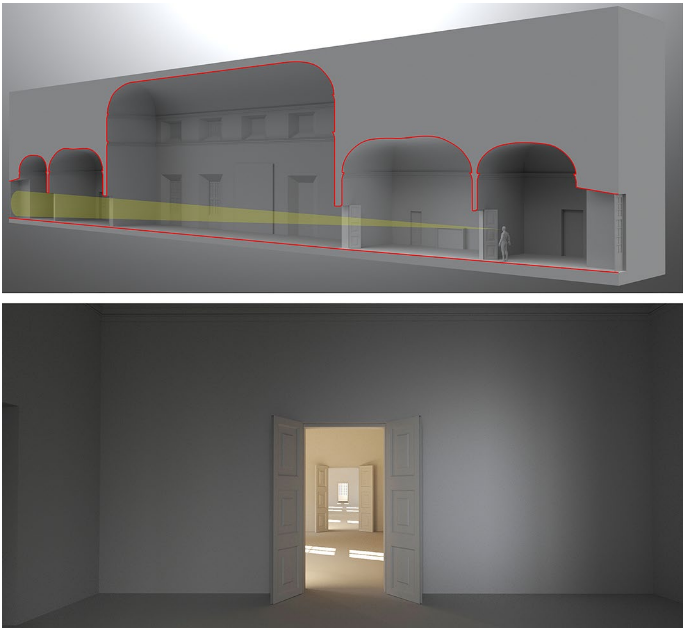

Fig. 13 (Above) a vertical perspective section of the complete virtual model with its perspective cone; (below) a human-height rendering that simulates this perception

Regarding the spatial effect of the rooms, the virtual model makes it easier to control the system of parameters on which this perception is based, such as light and point of view. For this capacity, a texture mapping process has been carried out, generating a realistic virtual model simulating the real perception of the architecture (Fig. 14). Finally, it was possible to create a virtual model of the reconstructed illusory architecture, making it possible to generate a 3D representation of the painting,

Fig. 14 Interior rendering of the virtual model of Camera di Giove

showing the results that emerged (Fig. 15a). The total height of the room, including the vault, is 6.5 m; the observer distance of the vault is 4.7 m above the floor and corresponds to the observer distance of the illusory architecture, whose height measures 7.5 m in the restitution. The illusory architecture contributes, therefore, leads to the impression of an additional 5.6 m in height. The model simulates the communicative aim of the artist and clarifies the perspective relationship with the existing space (Fig. 15b).

Conclusions

The study of quadrature framed in vaulted systems requires a complex path of analysis that must consider multiple factors related to the architectural space, defining the complex relationships between the existing space and the illusory architecture of the paintings. Here, the application of survey methodologies made it possible to achieve a detailed knowledge of the real architecture, analyzing its shape, and hypothesizing its genesis. The application of various 3D digital survey

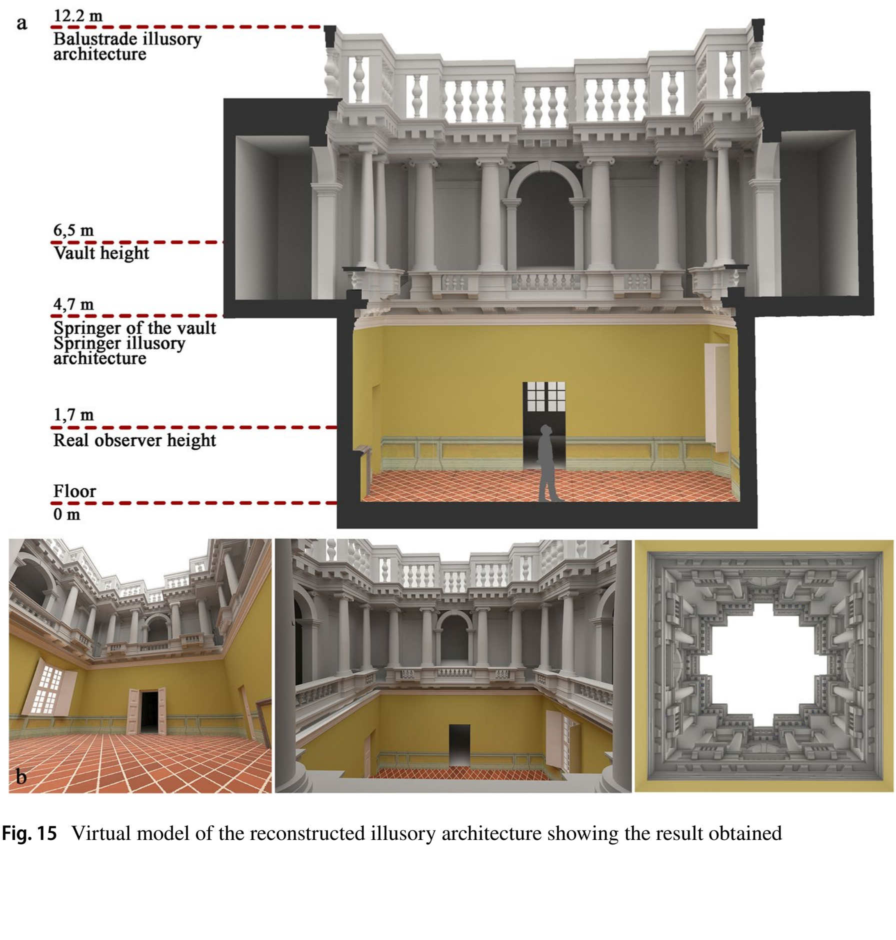

Fig. 15 Virtual model of the reconstructed illusory architecture showing the result obtained

techniques required validation of the acquired data, verifying the quality of the geometric information useful for the prospective analysis of the painting. In the quadratura study, the perspective analysis has been addressed to investigate both the painter's intentions and the spatial relationships between painting and space. The final phase of virtual representation made it possible to show some relational and perceptive characteristics of the space, highlighting the communicative and simulation capacity in a virtual environment. The suggested process, although presenting some cognitive gaps, has allowed a significant advance in the knowledge of the illusory system and its architectonic context.

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Authors' contribution All authors shared the whole research in all its steps. In the drafting of the article M.R. dealt with Introduction, Historical Background, Space Measurement and Analysis paragraphs; A.M.G. was responsible of Geometric Analysis and Virtual Architecture paragraphs; L.C. wrote the Conclusions. All images are by the authors.

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