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The Scuola Grande di San Marco in Venice between architecture and perspective reliefs: restitutions and applications of advanced fruition

The aim of the research was to investigate the facade of the Scuola Grande di San Marco in Venice through terrestrial photogrammetry and the procedures of perspective reversal, as well as digital representation and modeling. This investigation was conducted with particular interest in spatial reconstruction of the architectural elements defined in the perspective elevations.
The selection of photogrammetric methodology has permitted the acquisition of geometric data pertaining to the building that, in certain instances, are challenging to infer.
In addition to the projections and moldings of the Renaissance decorative apparatus, an orthogonal photographic mosaicking has been obtained that returns a planar projection of the main facade. The photogrammetric study was conducted in the lower portion of the elevation, where the illusionistic reliefs are situated. The reconstructions of these portions subsequently permitted the restoration of the plan and elevation in relation to the scene imagined in the marble perspectives, as well as the further three-dimensional modelling.
The integration of advanced sensing applications, perspective restitution, and digital representation of architecture enables the development of models that can be translated into augmented or virtual reality applications and physical-tactile replicas. These models can be utilized in a wider range of contexts, according to the specific needs of different categories of public (e.g., age, education, culture, disability, etc.).
They can serve as effective tools for dissemination and communication.

Keywords:
Scuola Grande di San Marco; Tullio Lombardo; illusionistic bas-reliefs; prospective restitution; advanced survey and representation

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INTRODUCTION

Among the most established methodologies for the study of cultural and historical heritage, the integration of photogrammetry and techniques of perspective restitution represents a valuable tool for research and documentation in the field of architecture.
Structure from Motion (SfM), a widespread practice today in schools of architecture and engineering, allows to acquire in a versatile and non-invasive way geometric and photometric data of buildings, decorations, and sculptural ornaments. This photogrammetric range imaging technique is capable of estimating three-dimensional structures from two-dimensional image sequences that may be coupled with local motion signals. In addition to providing high levels of three-dimensional plasticity, the technique allows for the acquisition of orthogonal projections of reconstructed models. For these reasons, it is an indispensable and fundamental tool in all investigations that consider prospective restitution. The latter is a practice that has been applied to photography but is often used for the study of paintings and frescoes. These works, which originated in the Renaissance, introduced the geometric perspective for the spatial definition of the figurative scene. The research presented here sought to investigate an architectural structure erected in the fifteenth century in Venice following a fire, whose facade is characterised by the work of Pietro Lombardo (1435-1515) and his son Tullio (mid-fifteenth century - 1532): the Scuola Grande di San Marco [1].
The SfM surveys of the entire main facade yielded orthogonal images of the lower level, which were employed to reconstruct inaccessible ornaments, assess the depth of reliefs, and recreate the illusionistic architecture traced in the marble perspective bas-reliefs.
The research has yielded the conclusion that digital models can be utilized in a variety of ways, including augmented, virtual, and tactile modes, by individuals with diverse user profiles. The output maquettes thus make the work more inclusive and accessible by exploiting the methodologies of drawing for interpretation and translation, thereby making the 3D artifacts available to the community.

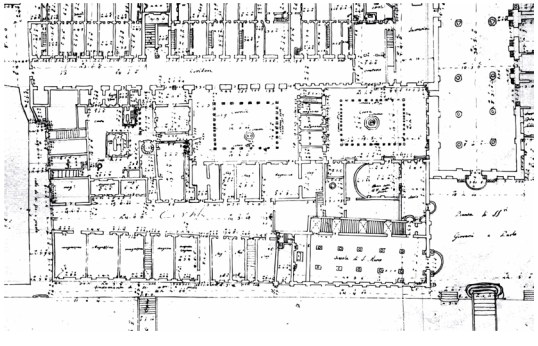

Fig. 1 - The ground floor of the convent of Saints John and Paul prior to the destruction and subsequent alterations (1800). A vector representation of the analogical document.

1. THE SCUOLA GRANDE DI SAN MARCO AND THE BAS-RELIEFS BY TULLIO LOMBARDO

The facade of the Scuola Grande di San Marco in the Castello district in Venice represents one of the pinnacles of Venetian Renaissance architecture. The edifice, situated within the complex, is renowned for its role in the renewal of the architectural style of the Venetian Great Schools. It inaugurated the era of the "ancient" built factories, employing the most skilled artisans of the period (Guidarelli, 2017, p. 43).
The Confraternity (one of six Great Schools established for charitable purposes in the lagoon city) was founded in 1260 at the church of Santa Croce. Nearly two centuries later, it erected a new headquarters next to the Basilica of Saint John and Paul. In fact, in order to increase the funds available after the considerable expenses incurred in the construction of their church, the Dominicans decided in 1437 to sell to the brothers of the School a plot of land and a number of small buildings situated in close proximity to the religious edifice. The congregation's conspicuous economic availability permitted the construction of a significant center, whose richly decorated main front was subsequently covered by marble. Following the fire of 1485, the first building remained only the portal (dated 1458). However, the reconstruction was swiftly initiated thanks to the support of the Council of Pregadi and on a project overseen by Pietro Lombardo, Giovanni Buora, and Mauro Codussi. In 1490, the protracted delays in the completion of the project, attributable to the relentless escalation in costs, compelled the School Council to replace Pietro Lombardo as the director of the construction site with Mauro Codussi. Codussi, five years later, successfully concluded the project.
The architectural plan of the edifice included the School, the Convent, and the chapel dedicated to the Blessed Virgin of Peace (Fig. 1). The School was accessed from the main portal, while the right door led to the monastery and the small church. The entrance to the school introduced the visitor to the great atrium, a vast space on the ground floor divided into three naves and flanked by the staircase of Codussi. This provided access to the Sala Capitolare. The remainder of the structure provided a series of functional spaces for the life and work of the religious community. The entrance hall is distinguished by two rows of five columns, each raised by a pedestal with a square base. Additionally, two pairs of half-columns are positioned on the front walls, a clear reference to the entrance prothyrum. The upper floor is supported by wooden shelves set into the walls and by flanges. The architectural composition and the stylistic elements evoke the grandeur of ancient basilicas and the characteristics of monumentality (Guidarelli, 2017, p. 48). The columns situated on pedestals at the entrance hall exemplify a clear and harmonious integration between the interior and exterior architectural elements of the building. This is also evident from the hierarchy between the three naves of the main and secondary rooms, which is then taken up in the structure of the architectural orders and in the design

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of the stone parties. The façade on the canal that develops along the foundations of the Mendicants responds to the scanning of the internal columns through the rhythm of the external pilasters with a ratio between the two systems of 2:1. This ratio is consistent with the findings of Sohm (Sohm, 1982, p. 147). In 1819, the edifice underwent a transformation, becoming an Austrian military hospital. This function was retained when the hospital was converted into a civilian facility in Venice.
Among the most notable features is the crowning double trilobate, which presents numerous stone niches, architectural parameters that are common in Venetian churches and the Upper Adriatic region. The illusionistic reliefs by Tullio Lombardo, which are designed and carved to adorn the lower register, contribute to the unique character of the facade of the Scuola Grande di San Marco. Two panels represent the events narrated by the Stories of Saint Mark (the "Healing of Anianus" and the "Baptism of Anianus") within a loggia constructed of pilasters and closed above by a coffered ceiling with floral motifs. In contrast, those positioned adjacent to the principal portal each portray a Marcian Lion within a gallery covered by a barrel vault embellished with lacunars.
The distinctive feature of these reliefs is the evident intention of the author to challenge contemporary pictorial trends. In fact, the sculptor creates these panels as if they were real windows, opening in the fabric of the walls. Beyond these windows, a space is perspectively delineated that is seamlessly integrated with the existing architectural framework. This space extends from the first floor to the background.

2. DIGITAL SURVEYING PROCEDURES

The objective of this research was to examine the facade of the Scuola Grande di San Marco through the application of terrestrial photogrammetry, perspective inversion procedures, and advanced representation techniques. This study focused on the analysis of ideal architectural forms defined in perspective bas-reliefs.
In addition to its intrinsic versatility in terms of time and cost, photogrammetry has been chosen for its ability to acquire a significant portion of the geometric data of the building, which is not easily deducible from an investigation carried out with a laser scanner. Indeed, the two parties in relief dedicated to the cycle of the "Stories of Saint Mark" are currently safeguarded by transparent plexiglass screens. They allow exclusive visual enjoyment of the works, but may alter data collection, including the identification of homologous points, and thus compromise the final result of the reconstruction.
The processing of two-dimensional images enabled the creation of a three-dimensional model of the facade, as well as its orthogonal projection. This latter was found to be particularly useful for subsequent prospective return surveys, as well as for the 2D representation of the same. The 395 photographs were captured using a Canon EOS 850D reflex camera with a variety of focal distances (18 mm to 135 mm) and exposure times. The images were captured with a constant distance between the camera and the subject, maintaining

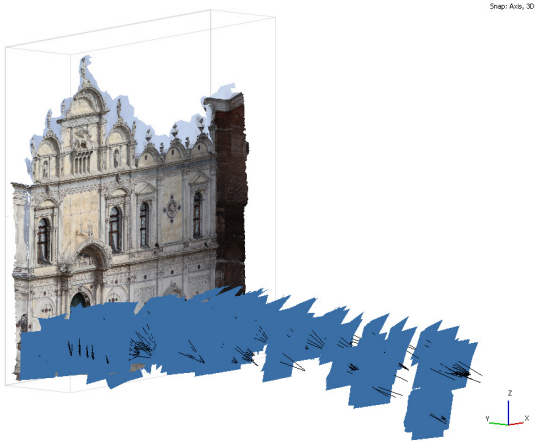

Fig. 2 - The calibration of the cameras in the photogrammetric software for facade reconstruction, straightening and digital ortho-projection.

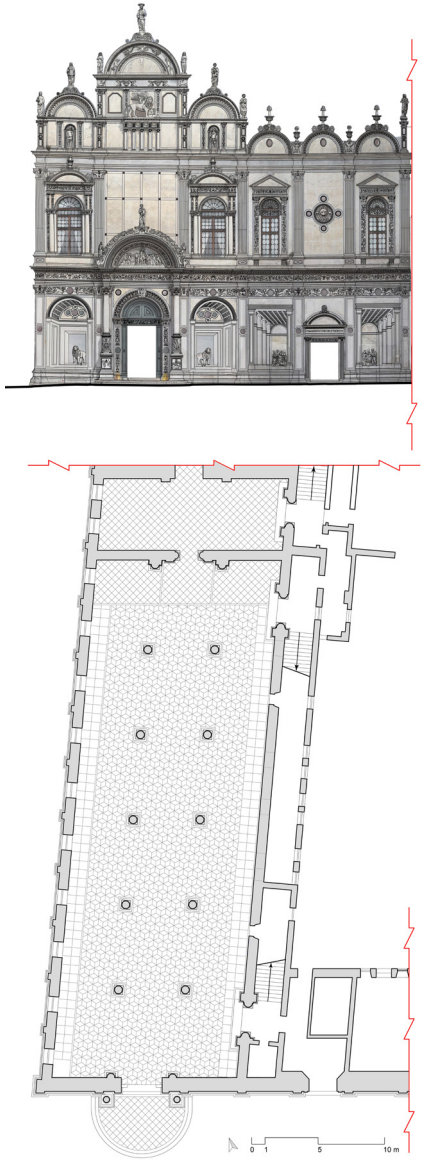

Fig. 3 - Planimetry and orthogonal mosaic of the facade of the Scuola Grande di San Marco obtained from the SfM procedure.

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Fig. 4 - Lower register of facade taken from the orthorectified image of the School.

parallel and convergent axes, as well as a frontal and upward or downward orientation (Fig. 2).
The primary critical issue during the survey pertained to the variable weather conditions and the non-constant diffuse ambient lighting of the façade, on the one hand, and the presence of people, which resulted in the concealment of some portions of the lower level of the building, on the other hand.
Prior to the implementation of photogrammetric software, a white balance correction was conducted on the images. Subsequently, all frames were calibrated in order to define the point cloud, mesh model, and textures. The achievement of the orthogonal mosaic of the façade was contingent upon the identification and removal of frames that did not guarantee the accurate interpretation of the images and, consequently, the integrity of the planar projection.
Moreover, the photogrammetric reconstruction enabled the definition of not only the 2D vector translation of the entire façade, but also constituted a tool for interpretation and integration in the representation of the irregular plan of the Venetian building (Fig. 3).

From the digital ortho-projection, the four different orthogonal parties relating to the "Marcian Lions" and the "Stories of St. Mark" were then extracted. This enabled the commencement of investigations into perspective inversion of the illusionistic bas-reliefs, the restitution of the plan and elevation, and the three-dimensional modeling of the scene represented through the marble inlays.

3. FROM THE GEOMETRIC STRUCTURE OF PERSPECTIVE APPARATUS OF BAS-RELIEFS TO THREE-DIMENSIONAL DIGITAL MODELS OF THE TWO BACKDROPS

In the facade of the Scuola Grande di San Marco, perspective panels by Lombardo virtually simulate two distinct scenic depths. The first is arranged to contextualize the "Marcian Lions", while the second accommodates the reproductions of "Anianus' Baptism" and "Healing".
The convergence of sculpted profiles to define the depth of architecture evoked in bas-relief clearly indicates the presence of two distinct perspectives. Initiating a process of prospective restitution on an orthorectified image of the two backdrops allows for the tracing of the measurements of the various architectural elements represented, thus enabling the reconstruction of their volumetric volumes in three dimensions.
The operations of perspective inversion can, in fact, record the conformation and dimensions of objects starting from a photograph of them. This is achieved by applying the principles of projective geometry to the construction of perspective images. The relative operating protocol is based on congruence between the photograph of an object and its perspective, which is realised by placing the centre of the lens as a centre of view and choosing the axis of the camera as the main visual ray. Given that the correlation between the photographic and geometric perspectives is not absolute, due to indeterminacy existing between the points of the object and those of the photographic image, it is only possible to resolve the above correspondence and make a perspective restitution by assigning metric data to the latter. Consequently, the investigation commenced with the objective of identifying the position and dimensions of the components that comprise the reference

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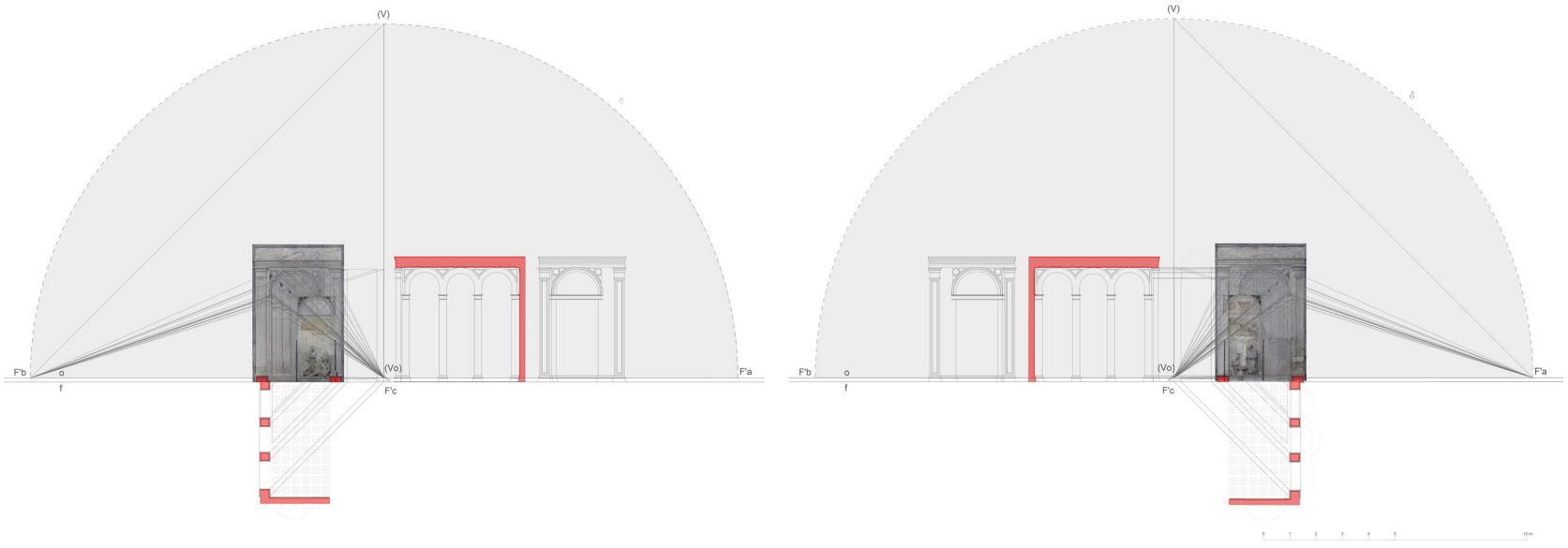

Figg. 5-6 - Perspective restitution of the "Baptism of Anianus" and the "Healing of Anianus".

system of the two geometric apparatuses. This constituted the initial phase of a comprehensive operation aimed at meticulously reproducing the planimetric and altimetric drawings of the scenarios. In the orthorectified image of the facade of the School obtained by photogrammetry, the sectors corresponding to the four sculptural panels (Fig. 4) have been assimilated to perspectives elaborated by the author as footprints to be followed to extrude the scenes from the stone slabs. Consequently, on these photographic compartments, the relative internal and external references of the two perspectives have been determined.
In the bas-relief entitled the "Baptism of Anianus" (Fig. 5), it is assumed that the position of the representation plan corresponds to the plane on which the author has placed the pilasters and the architrave that delimit the panel. In this context, the primary focus was on the common intersection of all the elements that extend beyond the coffered ceiling and are assumed to be perpendicular to the picture plane. At this juncture, however, the extensions of the profiles assumed to be orthogonal to the framework and belonging to the moldings of the pillars of the arches that open in the side wall do not converge precisely at the lower level determined for the ceiling of the barrel vault.
Once the horizon line has been identified, it has been possible to proceed with the refinement of its internal reference system. The two mutually orthogonal partitions that define the separation between the ceiling lacunae are assumed to have the same thickness in the two opposite directions. Consequently, in their intersections are outlined horizontal square surfaces whose diagonals extended to the horizon line are converged in the two points of distance. Once the distance between the latter and the main point had been defined, it was possible to determine the spatial interval between the picture and the point of view.
Subsequently, the fundamental line was positioned on the lower margin of this perspective box, thereby completing the external reference of the system. It is important to note that this line also crosses the vanishing point that governs the perspective of the lateral wall of the reliefs.
A comparable reference has been identified in the spatial representation of the scenario dedicated to the "Healing of Anianus" (Fig. 6), which exhibits the same peculiarities.
However, the lack of coincidence between the main points of the two scenes suggests the absence of a single perspective system. This system is probably doubled to increase the portion of architecture visible in the back wall and to contain the view inside the walls. This suggests a spatial dimension consistent with the geometry of the ceiling. The presence of two perspectives is not apparent, as the sculptor has chosen to entrust the degradation of the arches to a vanishing point that is situated in close proximity to the fundamental line.

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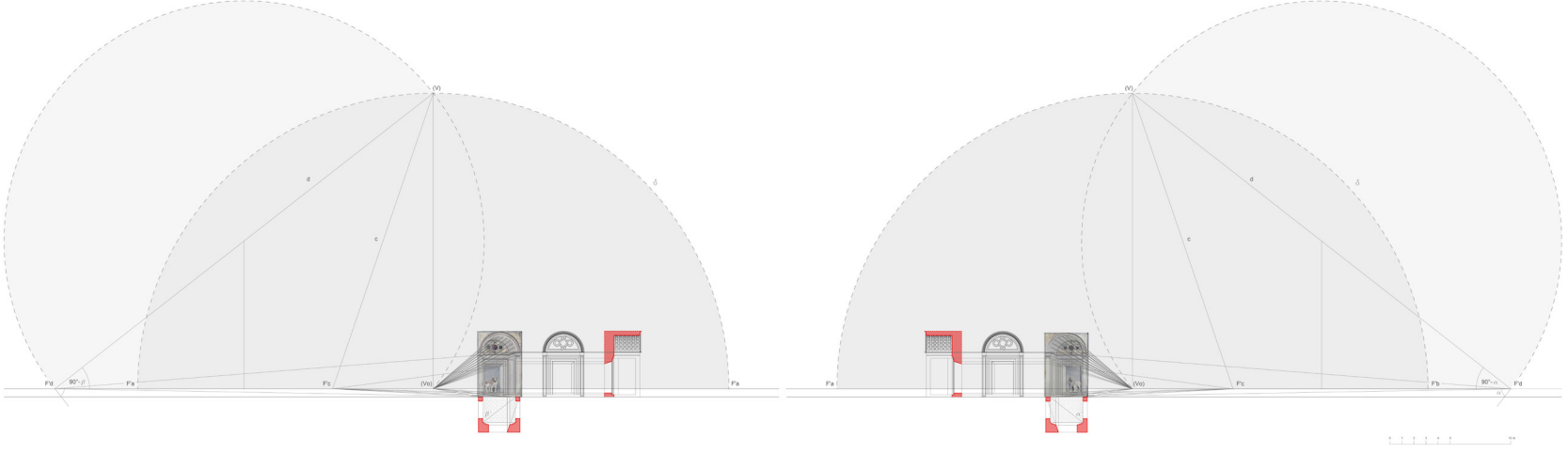
With regard to the bas-reliefs depicting the "Marcian Lions" (Figg. 7-8), the surface identified by the arch as delimiting the anterior surface of the cylindrical barrel vault has been assumed to represent the plane of representation. Furthermore, the position of the main point has been specified in accordance with the common convergence achieved by the extensions of those profiles of the coffered ceiling that can be reasonably assumed to be orthogonal to the representation plan.
It has been observed that the two main points, although they do not coincide precisely, are arranged at the same altitude. Therefore, if we disregard the insignificant distance recorded between these points, it can be assumed that preparatory drawings for these views have been drawn using a single perspective. Moreover, the identical altitudes of these limit points permitted the connection of the two bas-reliefs on the same horizon line.
In the bas-relief on the far left of the facade, the projection of the lacunars (which are believed to be squares) allowed for the accurate measurement of their dimensions (and that of the intervals that divide them) and the identification of the planimetric projection of lacunars, which is represented by the geometry of the vault.
Once the fundamental line had been traced along the lower margin of the bas-relief, the extension of the main distance was determined by means of an image of a horizontal rectangle whose objective sides were known and defined by the projection on the geometral plan of a grid drawn by the lacunars reproduced in the barrel vault. The perspective image of the rectangle exhibited two parallel sides and two orthogonal sides with respect to the representation plan. Consequently, in order to determine the main distance, it was necessary to identify the relative overturning point of view. This point was identified as the intersection between the perpendicular to the horizon conducted by the main point, and the arc of circumference built on the segment equal to the distance measured between the main point and the vanishing point of one diagonal of the rectangle that on geometral plan collects the projection of all lacunars. The main distance allowed for the identification of the station point proposed by the author for these reliefs: a position aligned with the main entrance of the school and situated at a distance equal to the height of its facade. The reference systems of all the bas-reliefs were perfected, and the operations of prospective reversal were initiated.
In the two reliefs dedicated to "Stories of San Marco", the architecture that has been configured by the operations of perspective reversal has defined a space that is defined on the sides by a system of pillars, which is concluded above by a simple molding on which three arches are set. The dimensions of these arches are not the same size because the extension of the central arch was found to be significantly smaller than the other two. The scene concludes with the appearance of a wall, the lower portion of which is adorned with a marble surface enclosed by pilasters and terminated by the same molding on the side pillars. In the upper portion, a stone slab, enclosed by an arched frame, is flanked by geometric decorations that bear resemblance to the motifs on the facade of the School. The perspective restitution composes the rhythm of the lacunar ceiling adorned with floral elements, yet it does not admit



Figg. 7-8 - Perspective restitution of left and right panels with the "Marcian Lion".

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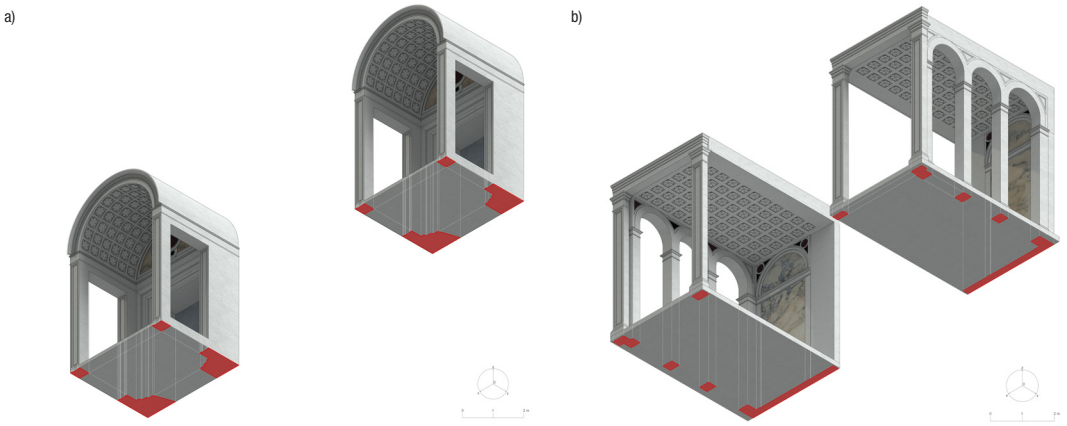

Fig. 9 - 3D model of the architecture represented in the "Marcian Lions" (a) and in the "Stories of Saint Mark" (b).

Fig. 10 - Perspective simulations of reconstructed illusionistic spaces compared to orthorectified images of the bas-reliefs.

information about the geometry of the pavement. This is because the relative depth of perspective coincides with the fundamental line. Furthermore, the planimetric interval between the restitutions of the "Stories of San Marco" is sufficiently wide to accommodate three additional arched frames. The false ceiling of these frames can be woven from a plot of lacunars that are identical to those identified by the perspective inversion. Consequently, the two reliefs are capable of evoking a larger and more continuous space, despite their ability to reproduce only portions adjacent to the side arches.

The process of perspective inversion has been applied to the scenic apparatus reproduced in the reliefs dedicated to the "Marcian Lions". This has resulted in the configuration of two openings in walls below the vault. One of these openings is lateral and is enclosed by two pillars with a square base. The other opening is located at the bottom of the scene and is marked by oblique countersinks practiced in the thickness of the only upright visible and the intrados of the above lintel. It is likely that these countersinks were used to increase the depth of the background.

The prospective restitution procedure has been completed, with digital modeling algorithms configured to evoke three-dimensional illusionistic spaces reminiscent of bas-reliefs. It is noteworthy that, for reasons of symmetry, only one of two parties represented in each architectural theme has been reconstructed (Figg. 9a-b).

Subsequently, in order to ascertain the congruence of the parameters acquired with the operations of prospective reversal, the prospective simulations of reconstructed illusionistic spaces have been digitally generated assuming points of view identical to those determined by prospective analysis.

The above perspectives, visualized in wireframe mode and superimposed on an orthorectified image of the facade of the School (Fig. 10), allowed for the evaluation of the adhesion between the photograph and the digital views. In particular, the electronic perspective of the "Baptism" and "Healing of Anianus" was analyzed. The perfect correspondence with the homologous elements represented was found in the lacunars, in the

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arches of the loggia, and in the decorative arch at the back of the scene. It was also ascertained that the perspectives of the parties with the Marcian Lions reproduced punctually most of the sculptural panel. Furthermore, the verification confirmed the design modalities of bas-relief fruition.

4. ONE MODEL, MANY SOLUTIONS TO DISCOVER ILLUSIONISTIC ARCHITECTURE

In order to facilitate a more comprehensive and accessible understanding of the findings derived from this geometrical and spatial investigation, the models of the illusionistic architectural parties have been proposed according to different modes of fruition. The aim was to enhance the understanding of these assets of the Venetian cultural and historical heritage, while also pursuing a scientific and educational purpose: to ascertain the efficacy of the procedure of construction and perspective inversion, which is a fundamental aspect of the discipline of representation.

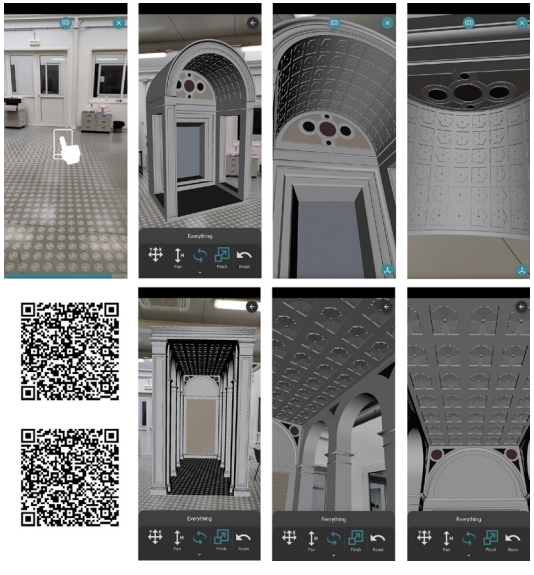

Fig. 11 - AR demo of 3D reconstructions. The models can be explored by activating the AR-media QR Code.

To overcome the limitations imposed by static renderings, a new approach was required. This entailed the utilization of sophisticated communication methodologies, including the implementation of augmented reality (AR), virtual reality (VR) and rapid prototyping (RP) techniques.
The initial two technologies, which are frequently conflated with one another, have the capacity to directly impact our visual perceptions. They serve to augment the real environment with information or to immerse the viewer through the visualization of real-time renderings. In order to gain a deeper understanding of the distinctions between the two visualization modes, two applications have been developed to analyze the differences between the two modes applied to two of the four illusionistic architectures of the Scuola Grande di San Marco.
In augmented reality, the user remains in the real world and experiences the two scenic depths through digital models that are superimposed, thanks to the camera, on the screen of laptops, smartphones, and tablets. The application is initiated through the identification of a trigger in accordance with marker-based AR technology. Once loaded, the user is able to interact with the digital architecture, scale, and rotate it to enhance visualization (Fig. 11) [2].
In contrast, in virtual reality, the user is entirely immersed in a fictional world, isolated from the real one through the use of a VR headset. The user is then able to move around and walk in a contained area or to approach areas that arouse their particular interest using the two controllers. The two models of illusionistic architecture have been designed to be displayed in full real scale, with the objective of facilitating a more accurate perception of the depth and proportions of the spaces designed by Lombardo. To achieve this, we employed video game software for the management of material maps and for the lighting of the scene. The three-dimensional reconstruction is visible with a virtual reality headset, which offers an interactive and immersive 360-degree experience (Fig. 12).
Finally, the final application considered was rapid prototyping. Currently referred to as 3D printing,

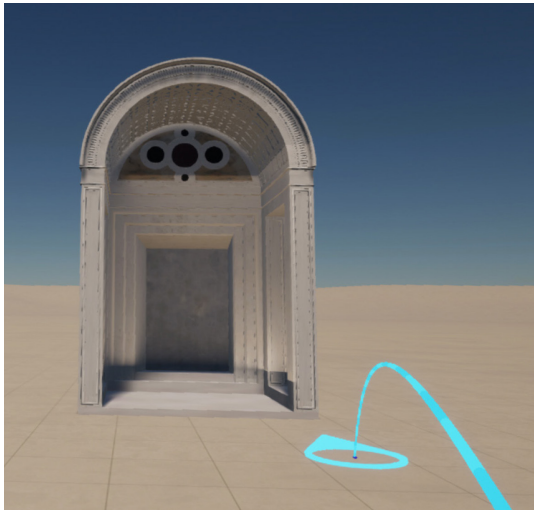

Fig. 12 - Virtual exploration through the VR headset.

this procedure enables the direct understanding of a digital model through its physical restitution. According to precise precautions in the design, preparation, construction, and finishing of the models in the round, they are particularly effective in transmitting geometric and compositional information, even to individuals with visual impairments. In this instance, the objective was to enhance the usability of the perspective scene of the bas-relief, which has been reconstructed by photogrammetry, through tactile exploration and to contrast it with the reconstruction achieved through geometric restitution (fig. 13a-b) [3].
In general, the two three-dimensional parts were constructed through both polygonal and solid modeling in order to meet the demands related to the output modes (AR/VR on the one hand, physical prototyping on the other). Particular attention has been paid to other aspects concerning the mode of use, including the scale of representation, the simulation of visual appearance (seamless texture and lighting), and tactile perception.

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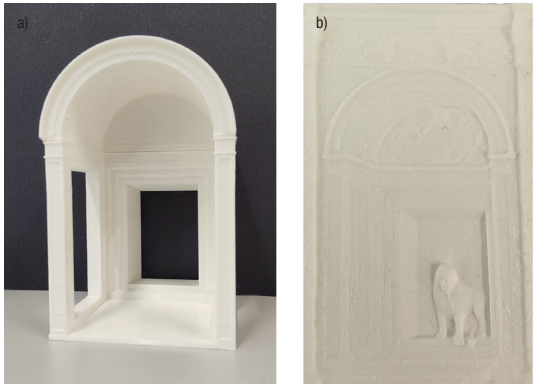

Fig. 13 - Physical models realized through rapid prototyping (RP): a) an all-round reconstruction; b) a photogrammetric reconstruction of one of the bas-reliefs.

RESULTS AND CONCLUSIONS

The present study aimed to integrate non-invasive survey technologies, perspective inversion, digital modeling, and advanced simulation of architectural heritage objects. In particular, the objective was to demonstrate the efficacy of a meticulous methodology for the documentation of historical assets and for their analysis within the context of representation.
The investigation procedures and the digital representation of the architecture contribute to the definition of models that can be translated into augmented or virtual reality applications and physical-tactile replicas, which can then be used in a wider variety of contexts according to the different categories of audience (age, education, culture, disability, etc.).
The models in question – physical, digital, augmented, and virtual – are valid tools that facilitate the dissemination and comprehension of architectural heritage. They enable the engagement of diverse user groups through a range of exploration approaches. The innovation lies in their versatility, whereby a single model can yield multiple solutions. It is evident that physical models reproduced to scale through rapid prototyping permit direct perception of a work through manipulation, thereby making it accessible even to hyposensitive subjects. Conversely, augmented and virtual reality offer the possibility of exploring architectures not only from a spatial/volumetric perspective but also from an immersive one through the simulation of materials and finishes, lighting, and interaction with objects in the scene.
In these terms, expanded fruition is to be considered a currently emerging paradigm that goes beyond the simple passive observation of digital spaces. It extends the user experience through the integration of immersive and interactive technologies, without obstacles and prohibitions due to protection and safeguarding, aspects that still very often limit the appreciation of cultural heritage. The experimentation conducted on illusionistic bas-reliefs has permitted a profound comprehension of the architectural characteristics, including those pertaining to scale of reproduction. This latter variable varies according to the specific needs of the users, with the objective of ensuring a more inclusive and comprehensive understanding of cultural heritage.

NOTE

[1] The survey and photographic acquisition activities, as well as the research proposal and the production of images related to the object of study, have been authorized by the Cultural and Museum Pole of the Scuola Grande di San Marco.

[2] A comparable study that employs three-dimensional reconstruction of a painted architectural masterpiece by Paolo Veronese and augmented reality is presented in the monograph authored by Silvia Masserano (2018).

[3] The issue of facilitating comprehension of perspective among individuals with visual impairments, through appropriate processes of synthesis, translation, and reproduction, is a topic of interest in several research areas, including the field of representation. This topic has been explored by Ansaldi (2023), Calandriello (2022), and Riavis (2020).

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