Digital Applications in Archaeology and Cultural Heritage 34 (2024) e00361

Contents lists available at ScienceDirect

Digital Applications in Archaeology and Cultural Heritage

journal homepage: www.elsevier.com/locate/daach

Pictorical reintegration of mural paintings to the irregular surface of the vault of the church of Santos Juanes in Valencia (Spain) through 3D digital techniques

Enrique Priego [a,b,*], José Herráez [a,b], José Luis Denia [a,b], María Joaquina Porres [a]

[a] Department of Cartographic Engineering, Geodesy and Photogrammetry, Polytechnic University of Valencia, Spain
[b] Heritage Restoration Institute. Polytechnic University of Valencia, Spain

ARTICLE INFO

Keywords:
3D models
Scanner laser
digital restoration
Cultural heritage

ABSTRACT

This study describes one part of the restoration project for the Antonio Palomino pictorial group, which is painted on the vault of the central nave in the church of Santos Juanes, in the city of Valencia (Spain). These fresco paintings were partially destroyed by a fire in 1936, and after several failed attempts for a correct restorative intervention, the greatest aesthetic merit of this church was lost and with it an important heritage element.

Now, after many years of the painting being in ruin, this integral restoration project has placed it in an aspect closer to how it was before its destruction. In this phase of the restoration, the areas of the damaged painting will be rectified using the two available black and white photographs and a 3D model of the vault. In addition, it will also describe how the paintings have been placed in their original locations. As follows, it is intended to restore the balance of the figures and allegorical characters on the vault of the temple and return this sample of Spanish Baroque to the new generations.

The solution presented in this study describes a novel methodology supported by geomatic techniques to carry out all the geometric control of the restoration. This have allowed the extensive pictorial program to fit three-dimensionally and relocate the paintings on the irregular surface of the vault, in the same place that the Spanish artist painted them.

1. Introduction

The artistic richness of the frescoes that Antonio Palomino (Córdoba, Spain, 1655–1726) left us in the vault of the church of Santos Juanes (Valencia, Spain), were created between 1699 and 1701 and once again, may be observed after this restoration is complete (Roig, 1994). This is the most ambitious pictorial composition (Roig, 1990) of this chamber painter of King Carlos II and disciple of the Spanish Baroque painter Juan de Valdés Leal.

Palomino was a man of religious training who devoted himself to the arts and letters, whose treatise '*Museo Pictórico y Escala Óptica*', consisting of three volumes published in Madrid in 1715, is probably the work that overshadowed his extensive work as a painter of both frescoes and altarpiece painting. The most representative pictorial works were the decoration of the *Plenary Hall* and the *Oratory* of the *Plaza de la Villa* in Madrid, he was also in charge of the decoration of the *Alcazar* (lost) and the tabernacle of the Carthusian monastery of the *Paular Monastery* (Madrid). He spent many years away from the court attending to commissions from different religious orders such as in Valencia, first in the *Basilica of the Virgin of the Desamparados*, in this one, the *church of Santos Juanes* and the design of the pictorial program of the *church of San Nicolás*. In Salamanca he painted the choir of the *Convent of San Esteban*, in Granada he decorated the *Sagrario de la Cartuja* and in Cordoba he painted five altar canvases for the new sacristy.

The artist displays in the vault of Santos Juanes a representation of the Celestial Glory connecting the decoration with the rest of the church by means of *quadratura* techniques based on the rule of perspective, where the painter opens the sky of the church to the divine sky. These are skills learned from his training in Theology and Philosophy as well as from his extensive career as a fresco painter and from his contact with leading painters such as Luca Giordano, who instructed him in the practice of foreshortened projection and clarified his palette of colours,

* Corresponding author. Department of Cartographic Engineering, Geodesy and Photogrammetry, Polytechnic University of Valencia, Spain.
E-mail address: epriego@upv.es (E. Priego).

https://doi.org/10.1016/j.daach.2024.e00361
Received 17 July 2023; Received in revised form 20 April 2024; Accepted 18 July 2024
Available online 26 July 2024

or with Francisco Rizi, Juan Carreño de Miranda and Claudio Coello, experts in the technique of *quadratura* or representation of feigned architectures. The first level of the iconographic program of the vault shows the twelve apostles and their allegories. The central part depicts God the Father and the Holy Spirit surrounded by heavenly choirs, saints and angels, populating the fictitious openings of the vault. The subject matter of the paintings conforms to the conventions of baroque rhetoric and its approach to immediate communication, with a message centred on the Holy Trinity.

The battered paintings, damaged by a fire during the Spanish Civil War on July 19, 1936 (Gris et al., 2019), were subsequently the object of a disastrous restoration by the Gudiol brothers' team between 1958 and 1963 (BOE). This attempted refurbishment was carried out by removing the mural painting from the vault of the church, which disassociated it from its surroundings, in addition to the repainting without reference to the original artwork. Subsequently, the painting was transferred to a plywood support, giving rise to 90 irregular panels that were anchored to the vault with nails and without consideration of their original location (Roig et al., 2020).

In this case study, unlike that carried out in other restorations with the work team of the Heritage Restoration Institute of the Polytechnic University of Valencia (restoration of the paintings of the Basilica of the Virgin or the paintings of the church of San Nicolas), the paintings are removed from their original position, which makes it necessary to treat it as a specific work for which a very particular and specific solution has been developed.

In the first phase of the project, results published by the authors in 2022 (Priego et al., 2022), the differential rectification of two black and white photographs which were taken before the fire, has been carried out. This shows an overhead view of the paintings on the vault, where digital images were rectified, stretched and scaled, and has been the key to carrying out this new restitution. In this phase, the mathematical development was carried out based on cartographic projections established via the geometric relationship between the irregular surface of the vault and the photograph (Priego et al., 2022).

The present work establishes and materializes the relationship between each pixel of the digital photograph (2D) with its corresponding spatial position in reality (3D). This correspondence has been carried out by means of a novel homologous process with a highly accurate 3D survey of the vault, the support for the paintings. Digital inpainting has grown in prominence as a result of improvements in image processing software and computer vision (Rakhimol and Maheswari, 2022).

After disassembling the paintings placed on the panels, which had accumulated moisture and bacteria over time (Zhabg et al., 2023), the original paint fragments have been cleaned and consolidated (Soriano, 2005). A single layer of original paint, 500 μm thick, remains on these wooden supports. This was achieved by removing the remains of glue, Gudiol's repainting, soot and the aftermath of the fire. In this way, that thin layer of paint has been transferred to a lighter and more stable carbon fibre support which is easier to maintain and less prone to paint deterioration (Blanco-Moeno, 2007; Cano and Chulia, 2018). This has an incomplete puzzle with fragments of the original painting and others that have been impossible to recover.

It is here, where rectified digital photography intervenes (Priego et al., 2022). First, mapping the damage to the affected areas. Subsequently, and based on the remains of the original painting and a colourimetric study of Palomino's work, those lost or damaged fragments have been coloured and the holes have been reconstructed by transferring the digital image printed on gel paper (Regidor et al., 2007). It is in this action that the new systems for recomposing wall paintings have been applied using digital image processing techniques and the errors of the previous intervention have been corrected. Digital restoration technology opens up a new field for wall painting and allows simulations before a painting is restored (Wei, 2014).

To provide geometric or dimensional validity, these images must be rectified to approximate a geometric representation free of perspective and scale errors (Priego et al., 2022). Georeferencing using topographic and photogrammetric techniques has made it possible to determine the correct location of each one of the fragments, both original and restored, and consequently the geometric fit of the entire pictorial ensemble on the vault.

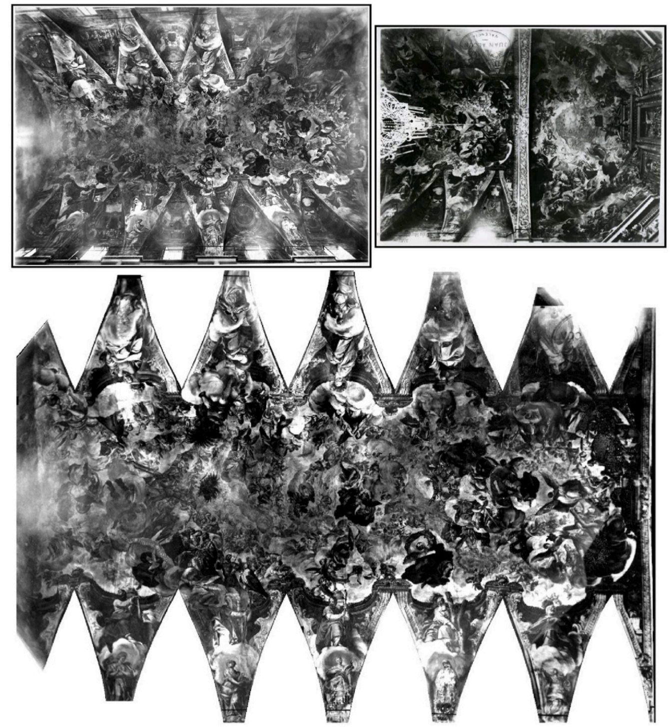


Fig. 1. Original photographs (J. Alcón) (a) Photo 1 (upper left) of the painting in the vault of central nave before the 1936 fire (b) Photo 2 (upper right) of the painting on the vault of presbytery before the 1936 fire (c) Rectified image (lower) of the paintings by Antonio Palomino in the complete vault of the church of Santos Juanes.

3D technology with its laser scanning systems has made it possible to obtain the digital twin of each of the restored panels and of the actual surface of the vault where they should be correctly located (Andreetto et al., 2004; Lee et al., 2010; Pesci et al., 2011; Alshawabkeh, 2020). This part of the process has been essential to virtually fitting the images of Palomino's mural painting (Fawzy et al., 2023), located in the different irregular fragments to the subsequent physical placement of the new panels on the vault, as well as the transfer of the images to the restored gaps.

Each of the restored panels have been placed using topographical techniques in their correct location in the vault of the church, which has made it possible, as if it were a puzzle, to locate the pictorial set to the author's original position.

2. Research aim

This research describes the geometric process in which the digital image of an analogic photograph, which has been previously rectified and scaled, aids the restoration of mural paintings being carried out on the irregular surface of the barrel vault of a church. In this part of the project, 3D technology is used, and an innovative transformation is applied that establishes the geometric relationship between objects in the plane (2D digital photography) and space (3D vault). This allows the image to be projected without deformations on the vault. The georeferencing and topographic stakeout of the fragments in which the paintings are currently found is also described.

Fig. 2. 3D mesh model of the vault.

3. Materials and methods

3.1. Rectified photography

The available graphic information consists of two photographs taken in 1920. The photographs were obtained with a large-format glass plate camera which was recorded on a film on a low-sensitivity glass support, which was used at that time.

The resolution is greater than 300 lpmm, deducted from the grain size of the analogic image. An algorithm has been developed that allows determining the radial distortion of the image from straight lines (Wu et al., 2023). The result of which is that the distortion is negligible, considering the size of the camera and its focal length.

The main photograph (Fig. 1a), with a size of 24 × 18 cm, offers an almost complete image of the paintings from an overhead view of the vault, using a nadir angle shot. The image of the second photograph (Fig. 1b), with a size of 18 × 13 cm, includes the area of the vault closest to the apse, which has been used to complete this common area with the main photograph.

Following what was published in 2022, where a projective rectification was applied to both photographs, which allowed the straightening and scaling of each of their images, the present work aims to generate a single rectified image to be transferred to the surface of the vault minimizing the metric deformations (Priego et al., 2022). These two images have been assembled into one, using the most defined part of each one. Therefore, this rectified digital image (Fig. 1c) provides two-dimensional (2D) graphical evidence of the pictorial composition that Antonio Palomino painted on the vault of this church.

3.2. 3D vault

The extensive pictorial program is developed on a curved surface defined by a semi-cylindrical barrel vault, 30.4 m long and 15.6 m in diameter. The pictorial surface is approximately 936 square meters, to which are added the 12 lunettes or secondary vaults (Galarza, 2009). Due to the construction itself and the passing of time, the surface of the vault is irregular and has certain bumps and deformations. Laser technology has made it possible to obtain its geometry with a high degree of precision and thus develop a 3D model of the cylindrical surface of the vault (Tobiasz et al., 2019; Liang et al., 2018; Diara, 2017; Vilceanu et al., 2013; Guarnieri et al., 2013; Foweles et al., 2003). The scan was performed from 12 positions with a Leica RTC360 scanner and a Trimble TX-6 scanner, obtaining a complete point cloud made up of 360 million points. As follows, the three-dimensional (3D) geometric information of the painting support is available (Fig. 2).

3.3. Panels

The painting is divided into irregular areas because of the previous restoration attempt, where after being removed from the vault of the church using the strappo technique, it was placed again on plywood supports. The Gudiol team tore the paint fragments from two-thirds of the vault, which were later placed on 90 panels.

In this new phase, the restitution will be made based on this division. Each panel is disassembled and taken to the laboratory of the Heritage Restoration Institute (UPV). Here a complete restoration will be carried out through selective cleaning with bacteria, and the elimination of the repainting to recover the original paintwork. Subsequently, the painting is then transferred to a new carbon fibre support, which is more stable and presents fewer conservation problems. In addition, this material can adopt the curvature of the area of the vault where it will be located, as it has been calculated from the 3D model of the vault surface.

Scanning each panel with a laser scanner allows for obtaining the detailed geometry of the surface defined by a cloud of points (approximately 940,000 points). A 3D survey is carried out on each of the restored panels (Fig. 3a). The 3D model will be used to make the three-dimensional fit in the vault before the stakeout. Three-dimensional modelling of cultural heritage with metrological documentation aims, is an expanding application area (Hoon and Hong, 2019; Porras-Amores et al., 2019; Aicardi et al., 2018).

In addition, with suitable software, its orthophotography is generated (Fig. 3b), and includes the 2D information to make its two-dimensional fit with the rectified photograph. This has allowed the

Fig. 3. Panel number 11 (a) Panel laser scanning (3D), (b) Panel orthophotography (2D).

mapping of the damaged areas and the colouring of the photograph.

4. Theory/calculation

The main objective of this research is to describe how the projection of the rectified image of the photograph (2D) materializes on the irregular surface of the vault (3D). In this methodology, a variant of the bilinear application has been developed that allows a transformation between the plane (x, y) and the space (X, Y, Z) (Abdel-Aziz and Karara, 2015).

The transformation would be the following [equation (1)]:

$$X = \begin{bmatrix} x & 1 \end{bmatrix} \begin{bmatrix} a_X & b_X \\ c_X & d_X \end{bmatrix} \begin{bmatrix} y \\ 1 \end{bmatrix}$$

$$Y = \begin{bmatrix} x & 1 \end{bmatrix} \begin{bmatrix} a_Y & b_Y \\ c_Y & d_Y \end{bmatrix} \begin{bmatrix} y \\ 1 \end{bmatrix}$$

$$Z = \begin{bmatrix} x & 1 \end{bmatrix} \begin{bmatrix} a_Z & b_Z \\ c_Z & d_Z \end{bmatrix} \begin{bmatrix} y \\ 1 \end{bmatrix} \quad [1]$$

where.

(X, Y, Z): coordinates of the position of any point in space.

(x, y): coordinates of the same point in the image.

(a, b, c, d): projective parameters.

The interesting thing about this transformation is that its application to certain straight lines in the image generates other straight lines in space, which applies to the sides of the triangles or rectangles that define the modelled surface of the vault. This solution is adapted to the problem of this work, since its application on the image of the photograph (x, y) generates in the vault (X, Y, Z) a regulated hyperboloid, which is one of the few surfaces in space which contains straight lines and is not a plane.

Developing equation (1), [equation (2)] are obtained:

$$X = x * y * a_x + x * b_x + y * c_x + d_x$$

$$Y = x * y * a_y + x * b_y + y * c_y + d_y$$

$$Z = x * y * a_z + x * b_z + y * c_z + d_z \quad [2]$$

Which can be written in matrix terms as [equation (3)]:

$$X = \begin{bmatrix} x*y & x & y & 1 \end{bmatrix} \begin{bmatrix} a_x \\ b_x \\ c_x \\ d_x \end{bmatrix}$$

$$Y = \begin{bmatrix} x*y & x & y & 1 \end{bmatrix} \begin{bmatrix} a_y \\ b_y \\ c_y \\ d_y \end{bmatrix}$$

$$Z = \begin{bmatrix} x*y & x & y & 1 \end{bmatrix} \begin{bmatrix} a_z \\ b_z \\ c_z \\ d_z \end{bmatrix} \quad [3]$$

If we have the image coordinates of 4 points that form a quadrilateral, and therefore there are not 3 of them aligned, the image coordinates would be organized in a matrix, and their corresponding counterparts in space would be organized in the matrix:

$$\begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \\ x_3 & y_3 \\ x_4 & y_4 \end{bmatrix} \quad [4]$$

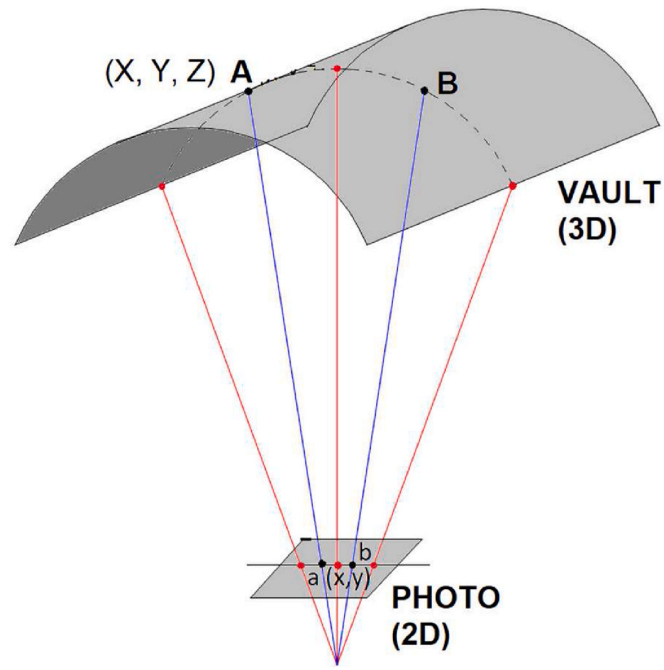


Fig. 4. Diagram of the relationship between a point in photography (2D) and a point in space (3D).

$$\begin{bmatrix} X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \\ X_3 & Y_3 & Z_3 \\ X_4 & Y_4 & Z_4 \end{bmatrix} \quad [5]$$

The application of equation (3) in space for each of the points, allows us to formulate 4 equations with 4 unknowns [equation (6)]:

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} = \begin{bmatrix} x_1*y_1 & x_1 & y_1 & 1 \\ x_2*y_2 & x_2 & y_2 & 1 \\ x_3*y_3 & x_3 & y_3 & 1 \\ x_4*y_4 & x_4 & y_4 & 1 \end{bmatrix} \begin{bmatrix} a_x \\ b_x \\ c_x \\ d_x \end{bmatrix} \quad [6]$$

If matrix (Rakhimol and Maheswari, 2022) is designated '*mat*':

$$mat = \begin{bmatrix} x_1*y_1 & x_1 & y_1 & 1 \\ x_2*y_2 & x_2 & y_2 & 1 \\ x_3*y_3 & x_3 & y_3 & 1 \\ x_4*y_4 & x_4 & y_4 & 1 \end{bmatrix} \quad [7]$$

Since the matrix is invertible, the coefficients are obtained as [equation (8)]:

$$\begin{bmatrix} a_x \\ b_x \\ c_x \\ d_x \end{bmatrix} = mat^{-1} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix}$$

$$\begin{bmatrix} a_y \\ b_y \\ c_y \\ d_y \end{bmatrix} = mat^{-1} \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix}$$

$$\begin{bmatrix} a_z \\ b_z \\ c_z \\ d_z \end{bmatrix} = mat^{-1} \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \end{bmatrix} \quad [8]$$

Unifying these 3 equations in a single matrix equation shows what, the bilinear application would look like [equation (9)]:

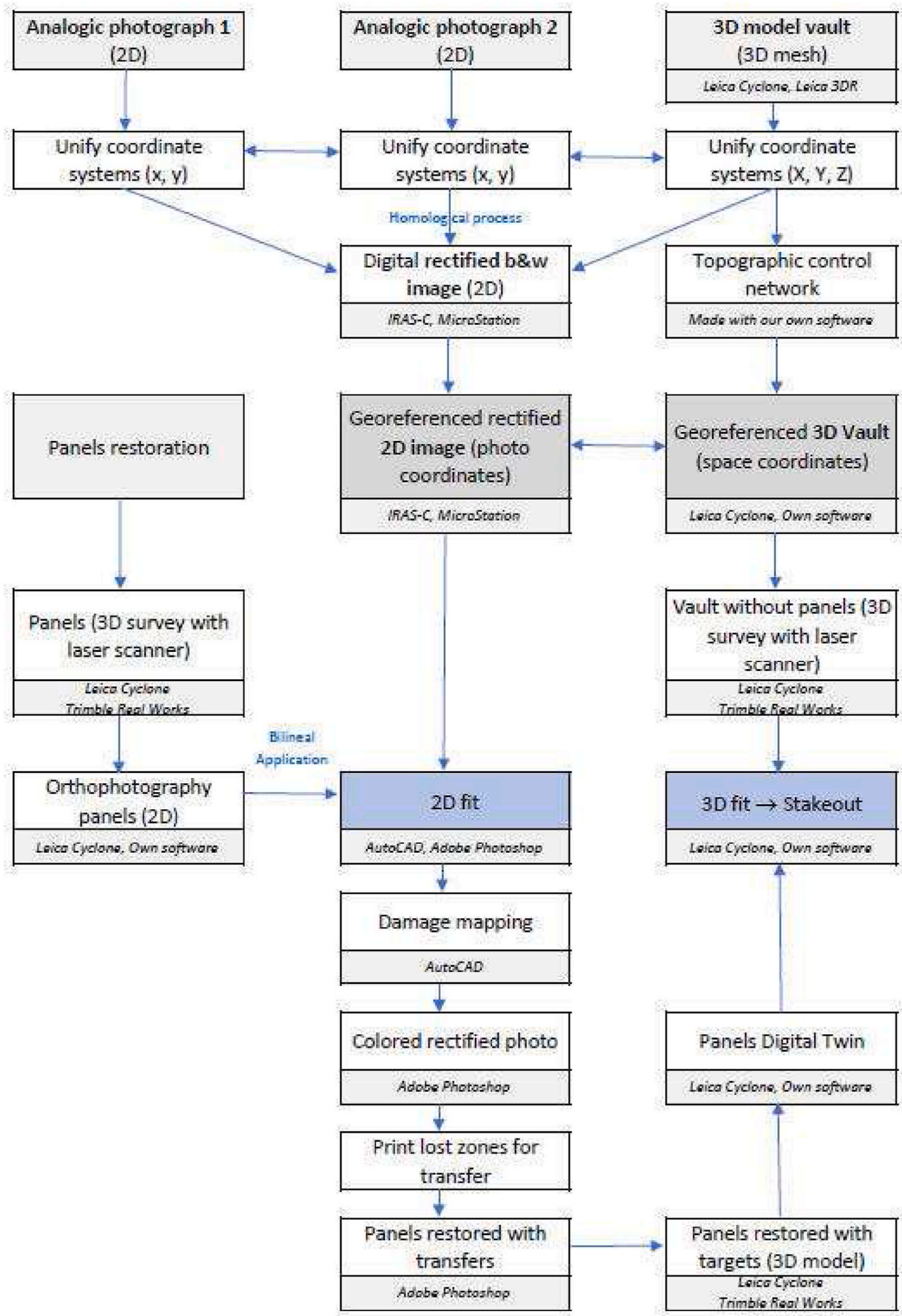


Fig. 5. Workflow.

$$\begin{bmatrix} a_x & a_y & a_z \\ b_x & b_y & b_z \\ c_x & c_y & c_z \\ d_x & d_y & d_z \end{bmatrix} = mat^{-1} \begin{bmatrix} X_1 & Y_1 & Z_1 \\ X_2 & Y_2 & Z_2 \\ X_3 & Y_3 & Z_3 \\ X_4 & Y_4 & Z_4 \end{bmatrix} \quad [9]$$

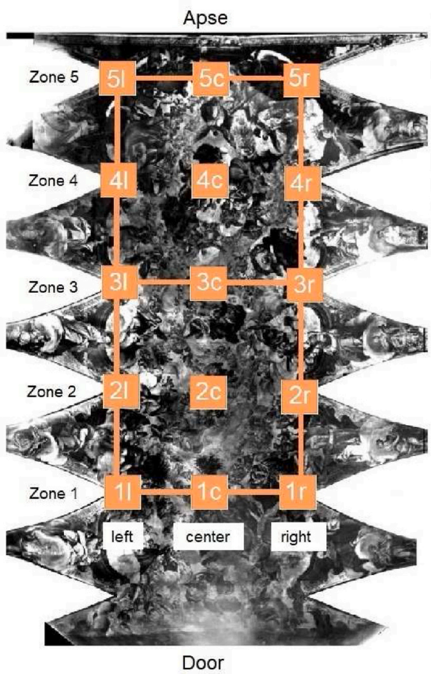
5. Results and discussion

As a starting point, there is a rectified, straightened, and scaled photograph, which contains the black and white image of the pictorial composition made by Antonio Palomino, as well as the geometry of the surface of the vault, containing the paintings, (Priego et al., 2022), which can be considered as a quasi-cylindrical surface concluding that, it is developable. The image of photography provides two-dimensional (2D) graphic information and the dome surface three-dimensional (3D) geometric information (Fig. 4).

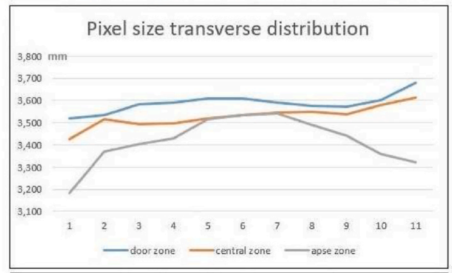
The main objective is to project the image of the rectified photograph on the irregular 3D surface of the vault with the minimum possible deformations (Dellepiane and Scopigno, 2013). This digital and virtual solution must materialise in this process of restitution of the paintings. This research aims to correctly locate each of the restored fragments of painting in the vault so that it can be admired by the viewer, bringing them closer to the sensations that the original composition could raise at its creation and thus establishing its permanence in time. Despite not having been able to rescue the original colours, since the paintings suffered from the high temperatures of the fire and producing chemical and pigmentation changes in the images, an attempt can be made to return this trace of history to this artwork.

A graphic version of the workflow is provided in Fig. 5, where the software used in each of the processes is also indicated.

A numerical analysis of the results obtained is carried out before



	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Left side	3,521	3,561	3,427	3,429	3,186
	3,536	3,531	3,515	3,479	3,371
	3,584	3,543	3,492	3,421	3,404
	3,592	3,561	3,498	3,484	3,430
Vault center	3,609	3,568	3,519	3,504	3,517
	3,609	3,572	3,535	3,549	3,533
	3,592	3,571	3,547	3,562	3,542
	3,576	3,567	3,550	3,512	3,489
	3,570	3,570	3,538	3,510	3,439
	3,600	3,600	3,580	3,465	3,357
Right side	3,680	3,680	3,611	3,542	3,320



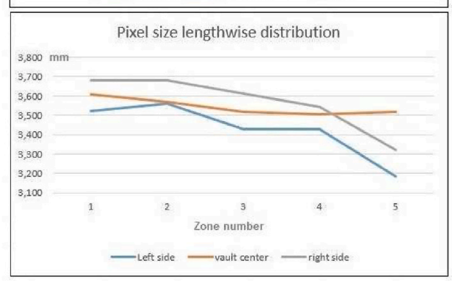


Fig. 6. Numerical and graphical analysis of the obtained results: (a) Spatial distribution of control areas. (b) Table where the magnitudes in millimetres (mm) of the pixel size are determined as a function of its spatial location in the dome. (c) Graph of spatial distribution in transverse direction (d) Spatial distribution graph in longitudinal direction.

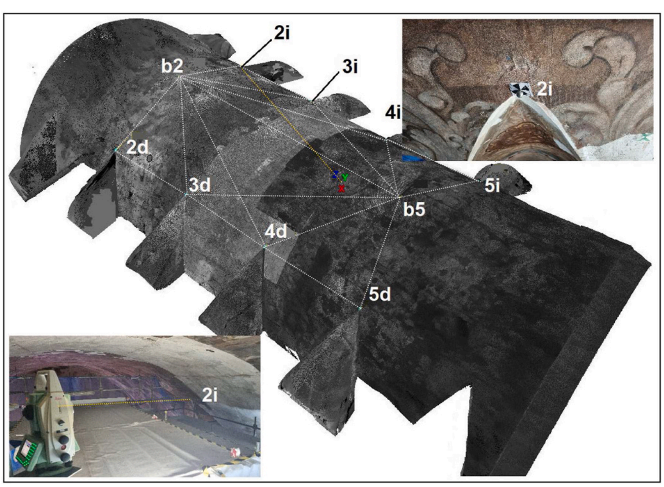


Fig. 7. Control topographic network. The network is made up of 10 vertices, 4 placed in right lunettes (2d, 3d. 4d and 5d), 4 placed in left lunettes (2i, 3i, 4i and 5i) and 2 placed in the vault (b2 and b5). In the upper right photograph, a spherical element is shown, and in the lower right photograph, the total station observing the spherical element 2i.

approaching each stage of the work. It is established that the accuracy achieved depends on the accuracy of the digital model of the vault and the quality of the image. For this purpose, it is considered that the accuracy of the digital model depending on the instrumentation used (laser scanner systems) can be estimated at 5 mm; while the accuracy of the image is determined by the pixel resolution of the image (3 mm).

To quantify the errors, different zones of the rectified photograph are projected, evenly distributed over the entire work area, applying the algorithm developed in this research, and the resolution in mm of each of the pixels of the photograph on the vault is determined.

Fig. 6 below shows the variation in spacing between consecutive pixels, or in other words, how much a pixel of the rectified photograph occupies on the dome, depending on the position it occupies on the 3D surface of the dome.

The results show that each pixel covers an area of 3–4 mm over the vault, with a range within the values established a priori and known depending on the camera and the position and angles from which the two available photographs were taken.

5.1. Coordinate system

In the first phase, a precision topographic network has been implemented, observed, and calculated, in order to have the entire system georeferenced. The network is materialized by points defined by spherical elements, whose centre is invariant, located at the vertices of the lunettes and keystone of the vault, with a homogeneous spatial distribution (Fig. 7).

In the observation of the topographic network, a Leica TS-30 total station has been used, motorized and with an angular precision of 0.5'' and a precision of 0.6 mm + 1 ppm in distances to the prism (2 mm + 2 ppm to any surface). The equipment has previously been calibrated and the constant for the distance measurement of all aiming elements has been calculated. The inverse intersection method has been used, and it has been calculated and adjusted using least squares. Thereby, coordinates are provided to all the elements in play: the rectified photograph, the vault, and the panels.

5.2. 3D model of the vault

The restoration process is carried out in stages, distinguishing between disassembly cycles for damaged panels and assembly cycles for

Fig. 8. 2D fit, assembly of the orthophotography of the panels in the rectified photograph (a) Montage of the first phase that includes 5 rows and 27 numbered panels. (b) Detail of the union of panels numbers 14 and 15. (c) Integration and colouring of panels 14 and 15.

restored panels. In each of these cycles, a strip of panels is restored at the same time, normally in bands between lunettes.

Although initially the geometry of the vault was intended to be constructed as a semi-cylindrical surface, after its measurement it was verified that there are many irregularities, and that it is more appropriate to represent these areas of the vault from the actual measured surface.

Once the panels of a section have been removed, the vault is scanned with a Trimble TX-6 laser scanner, which allows for obtaining a very dense cloud of points that correspond to that irregular surface. This point cloud is processed to obtain triangle meshes that generate the 3D model of the area of the vault without panels, between the restored and

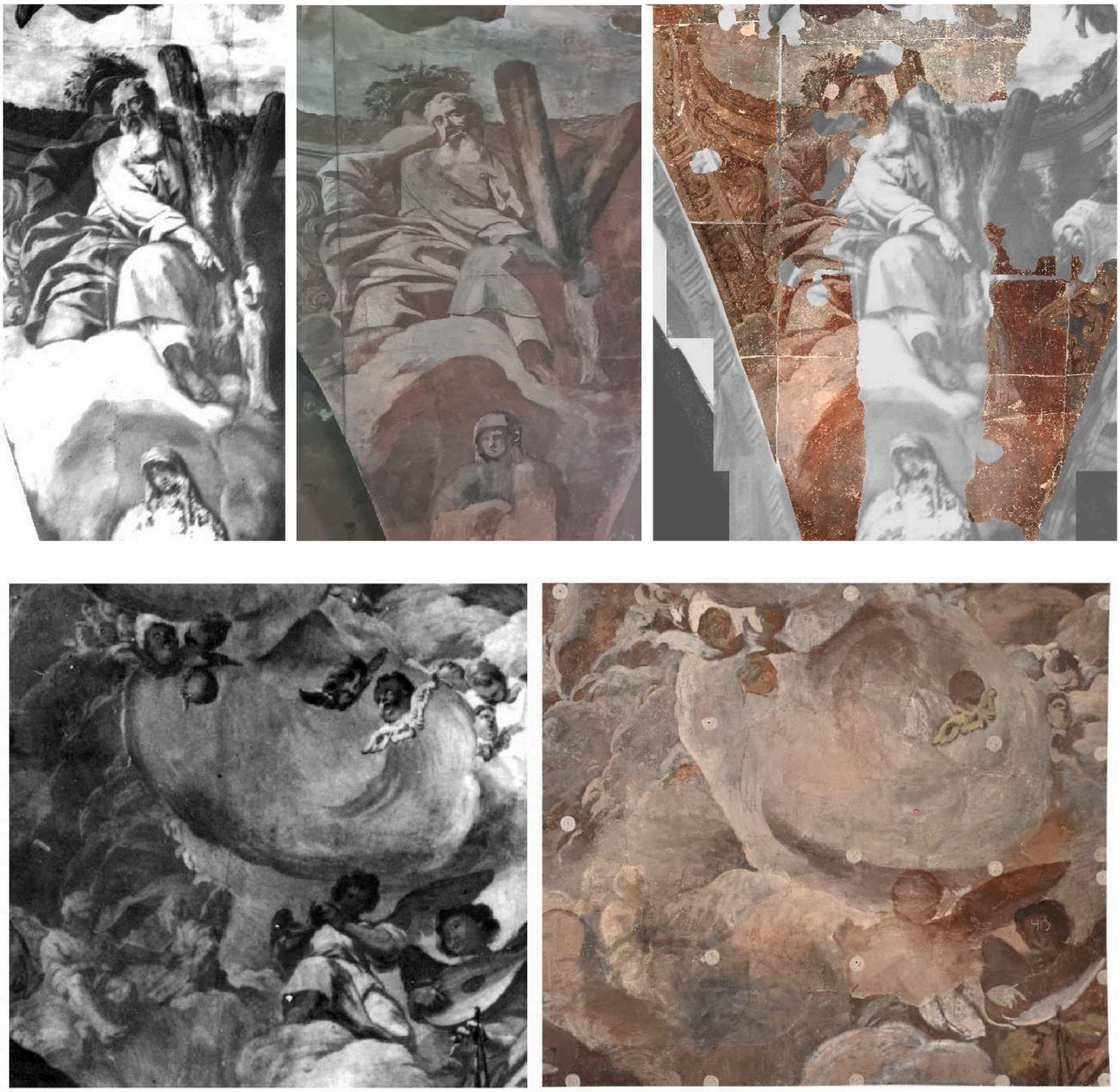


Fig. 9. Examples of the unfortunate interventions of the 1960s: (a) Figure of Saint Andrew: on the left, image of b&w photograph (1920), in the centre, previous intervention (1960), on the right, what is left of the original paintwork fitted to the rectified photograph (2024). (b) Comparison between the photograph of the 1920s and the previous intervention, where some of the angels' figures disappear and others are not represented as they were.

unrestored panels.

The spherical elements visible in each scan, reference each partial survey of the vault in coordinate system. 3D geometry of the surface where the newly restored panels will be located is available, and likewise, the curvature that the new carbon fibre support of each panel must acquire is determined so that it adapts perfectly to the area of the vault where it will be installed.

5.3. 3D model of the panels

The division of the painting, when it started in the previous intervention, was carried out without any geometric criteria, which gave rise to panels with irregular shapes. After their numbering, a topographical survey is carried out to determine their current location in the vault, a photographic record and a laser scanner are made to document the initial state of the panels.

In this phase of the process, the restoration itself begins, and one by one, the panels are photographed with ultraviolet filters to recognize repainting and other inappropriate additions. The bio-cleaning process begins, which consists of the use of selected microorganisms (probiotic bacteria) for the selective cleaning of dirt from artworks sustainably and ecologically, in addition to the use of surfactant-free emulsions to remove non-original repaints and lasers to remove difficult scabs.

Once the original painting fragments which are to be preserved have been consolidated, they are placed on the new carbon fibre supports, cutting its perimeter according to the shape of the restored painting.

After this process, the newly restored panel is scanned and photographed. On the one hand, the 3D model of each panel is obtained, which will be used to carry out the three-dimensional fit in the vault. On the other hand, its orthophotography is obtained by a 2D photograph, in which all the elements are at the same scale, free from errors and deformations. In the image obtained, the areas of the original painting are well-defined, and the lost areas or gaps have been cut out. This orthophoto will be used to make the two-dimensional fit with the rectified photograph.

5.4. 2D fit of the restored panels

This is the most complex phase of this study and is where the new technique developed is applied. In this part of the project, the

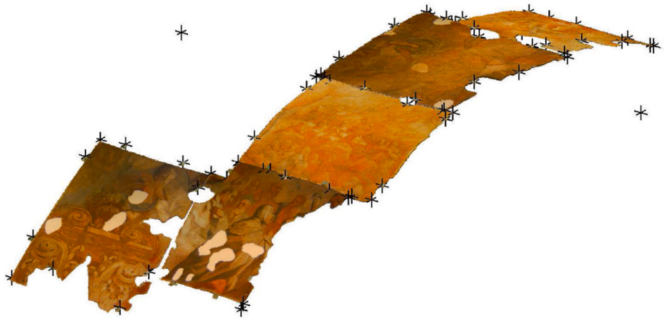


Fig. 10. Virtual 3D fit of panels 4, 5, 6 and 7 (row 1) and panel 11(row 2).

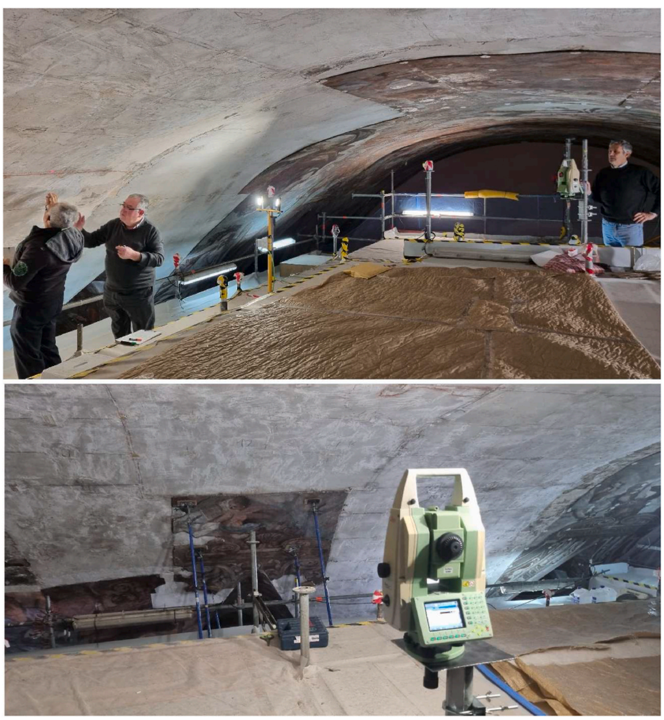


Fig. 11. Photographs of the stakeout work of the surveying team. 3D stakeout panel 11.

planimetric fit of the orthophotography of each panel is made with the rectified photograph that contains the image of the entire pictorial composition and the bilinear application developed in this work is used [equation (9)].

The correct selection of at least 4 homologous points, both in the orthophotography of each panel and in the rectified photograph, will allow the combination of the images of both. The image resulting from this 2D fit is used to map the damaged areas (they are georeferenced) and to colour the rectified photograph (Fig. 8).

With these results, it has been possible to locate the areas where the important differences were made in the previous intervention. The repaints from the 60s in the artwork lack the necessary technical knowledge for an authentic restoration, as well as reproduce the original lines, which has complicated this reintegration work. Some examples are shown in Fig. 9.

The orthophotography of each one of the panels makes it possible to transfer the current colour of the paintings, which differs from the original after suffering the high temperatures of the fire. A part of the restoration team has carried out a colourimetric study, which allows an exhaustive analysis of the colour and iconography of Antonio Palomino's work to be carried out (Dal Fovo et al., 2023). In addition to his great literary work '*El Museo Pictórico y Escala Optica*' (Palomino, 1947), published in 1715, there are references to his painting in different official and religious buildings in Spain. This has made it possible to colour digital and rectified photography.

For the areas of missing paint, each gap has been printed on a 1/1 scale on gel paper (this material is rigid but becomes elastic when wet) obtained from the coloured orthophotography. Once the gap has been stuccoed, the image is transferred by pressure and the injection inks remain in that area, which also persists after removing the paper (Regidor et al., 2008).

5.5. 3D fitting and 3D stakeout of the restored panels

When the panel is clean, integrated, and ready for placement, some stakeout targets are placed on its edges and the already restored fragment is scanned with a laser scanner. Thus, the geometry of the panel is available, fundamentally its curvature and its edges, as if it were a 3D puzzle piece (Fig. 10). Likewise, the geometry of the scan of the area of the vault where these pieces must be placed is available.

In this last phase, the transformation between the 2D plane (photograph) and the 3D space (vault) is carried out (Navarro et al., 2018). Using the bilinear application variant developed in this research, the coordinates of the targets on the vault are calculated, which will allow the location of each restored panel in the same area of the vault where Antonio Palomino painted it.

With point cloud treatment and 3D modelling software, it is possible to visualize possible solutions virtually and digitally for the fitting of the pieces together and on the vault. Using topographic survey techniques and using the Leica TS-30 automatic total station, each of the panels with their adjacent ones are placed, as if it were a puzzle (Fig. 11). Once its installation is finished, we proceed to the pictorial retouching of the joints, giving continuity to the entire composition and restoring the balance of the pictorial ensemble.

6. Conclusions

The pictorial work of Antonio Palomino on the vault of the church of Santos Juanes in Valencia (Spain) has been waiting for a solution for almost 90 years and the execution of this proposal is granting an integral intervention that will recover the valuable fragments of fresco mural painting that are still preserved. In this paper, we proposed an improvement in the digital transfer of images. Using the only available analogic photograph that offers an overhead view of the paintings in the vault, its scaled image could be transferred to real size with the minimum metric deformations and reconstruct the original forms of the drawing with the greatest possible fidelity.

A photograph, analogic or digital, provides a lot of information and through photogrammetric techniques, it is possible to obtain the geometries (real measurements) of the objects that are defined in it. The use of photographic images as reintegration material allows us to approach the original faithfully, without supplanting the painting or falsifying it. The digital rectification of the photograph, together with the measurement with laser scanner technology, to obtain 3D models with precision and a high degree of detail, has allowed the development of a variant of the bilinear application that solves the transformation between points in-plane (x, y) and points in-space (X, Y, Z). Thanks to the existence of historical photographic material, it has been possible to apply this technique and develop it in the real case of this mural painting, contributing to the preservation of artistic historical heritage.

The results showed that our methodology allows integration with a high degree of precision, allowing the original painting with the fragments to be restored by transferring ink impressions, improving the previous restoration and satisfying as far as possible the irreparable damage caused by the 1936 fire.

CRediT authorship contribution statement

Enrique Priego: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **José Herráez:** Conceptualization, Data curation, Formal analysis, Investigation, Software, Writing – original draft. **José Luis Denia:** Conceptualization, Methodology, Visualization, Writing – review & editing. **María Joaquina Porres:** Data curation, Formal analysis, Investigation, Validation, Writing – review & editing.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Acknowledgements

The results of this research are included in the project 'Contrato para la restauración de las pinturas murales, esculturas, estucos, ornamewntación y retablos del conjunto de la iglesia de Santos Juanes de Valencia' between 'Universitat Politècnica de Velencia' and 'Parish of Santos Juanes of valencia' funded by 'Fundación Hortensia Herrero'. The authors would like to thank the patron-president of the foundation Hortensia M[a] Herrero, professors and researchers Pilar Roig and José Luis Regidor, and all the restoration team, for the trust they have placed in our geomatic team.

References

Abdel-Aziz, Y.I., Karara, H.M., 2015. Direct Linear Transformation from comparator coordinates into object space coordinates in close-range photogrammetry. Photogramm. Eng. Rem. Sens. 81 (2), 103–107. https://doi.org/10.14358/PERS.81.2.103.

Aicardi, I., Chiabrando, F., Marial Lingua, A., Noardo, F., 2018. Trends in cultural heritage 3D survey: the photogrammetric computer vision approach. J. Cult. Herit. 32, 257–266. https://doi.org/10.1016/j.culher.2017.11.006.

Alshawabkeh, Y., 2020. Color and laser data as a complementary approach for heritage documentation. Rem. Sens. 12 (20) https://doi.org/10.3390/rs1220.

Andreetto, M., Brusco, N., Cortelazzo, G.M., 2004. Automatic 3D modeling of textured cultural heritage objects. IEEE Trans. Image Process. 13 (3), 354–369. https://doi.org/10.1109/TIP.2003.821351.

Blanco-Moeno, F., 2007. Corrección, adaptación y tratamiento digital de las pinturas murales de Antonio palomino, presentes en la bóveda de la real parroquia de los Santos Juanes de Valencia, TFM.

BOE. Orden de 18 de agosto de 1960 por la que se aprueban obras en la iglesia de los Santos Juanes de Valencia, URL: https://www.boe.es/boe/dias/1960/10/18/pdfs/A14502-14503.pdf.

Cano, J.M., Chulia, A., 2018. Historical and constructive analysis of los Santos Juanes church in valencia. React. Proact. Architect. 408–413. ISBN: 978-84-9048-713-6.

Dal Fovo, A., Mattana, S., Ramat, A., Riitano, P., Cicchi, R., Fontana, R., 2023. Insights into the stratigraphy and palette of a painting by Pietro Lorenzetti through non-invasive methods. J. Cult. Herit. 61, 91–99. https://doi.org/10.1016/j.culher.2023.03.002.

Dellepiane, M., Scopigno, R., 2013. Global refinement of image-to-geometry registration for color projection. Digital Heritage Int. Congress 1, 39–46.

Diara, F., 2017. Conservation analysis using photogrammetric post processing techniques: the example of Early Medieval low relief in SS. Assunta e S. Bartolomeo Church in Badia Prataglia, Tuscany. In: Proceedings of the 22nd International Conference on Cultural Heritage and New Technologies. ISBN 978-3-200-06160-6.

Fawzy, H., Kandeel, R., Farhan, M., 2023. Detection of deformations in reinforced concrete structures using modern surveying techniques. Alex. Eng. J. 70, 191–218. https://doi.org/10.1016/j.aej.2023.02.030.

Foweles, P.S., Larson, J.H., Dean, C., Solajic, M., 2003. The laser recording and virtual restoration of a wooden sculpture of Buddha. J. Cult. Herit. 4, 367–371. https://doi.org/10.1016/S1293-2074(02)01141-X.

Galarza, M., 2009. La restauración barroca de la iglesia de Santos Juanes de Valencia. La bóveda tabicada que soporta los frescos de Palomino. Acta del VI Congreso nacional de Historia de la Construcción 523–531.

Gris, M.A., Caraball, M.A., Santamarina, V., 2019. Religion and Civil War. Parish church of Los Santos Juanes de Valencia, 11th European Symposium on Religious Art. Restoration and Conservation - ESRARC 2532–4381. ISNN.

Guarnieri, A., Milan, N., Vettore, A., 2013. Monitoring of complex structure for structural control using terrestrial laser scanning and photogrammetry. Int. J. Architect. Herit. 7 (1), 54–67. https://doi.org/10.1080/15583058.2011.606595.

Hoon, Y.J., Hong, S., 2019. Three-dimensional digital documentation of cultural heritage site based on the convergence of terrestrial laser scanning and unmanned aerial vehicle photogrammetry. Int. J. Geo-Inf. 8 (53) https://doi.org/10.3390/ijgi8020053.

Lee, I.S., Lee, O.L., Park, H.J., Bae, K.H., 2010. Investigations into the influence of object characteristics on the quality of terrestrial laser scanner data. J. Civ. Eng. 14, 905–913. https://doi.org/10.1007/S12205-010-0986-7.

Liang, H., Li, W., Lai, S., Zhu, L., Jiang, W., Zhang, Q., 2018. The integration of terrestrial laser scanning and terrestrial and unmanned aerial vehicle digital photogrammetry for the documentation of Chinese classical gardens – a case study of Huanxiu Shanzhuang, Suzhou, China. J. Cult. Herit. 33, 222–230. https://doi.org/10.1016/j.culher.2018.03.004.

Navarro, P., Yudici, S., Herráez, J., Denia, J.L., Martín, M.T., Rodríguez, J., 2018. Restoration of paintings on domes with non-developable geometry (los Santos Juanes church in Valencia). Int. J. Architect. Herit. 12 (2), 169–177. https://doi.org/10.1080/15583058.2017.1356946.

Palomino, A., 1947. In: El Museo Pictórico Y Escala Óptica. Aguilar tomo II, VII-IV-III.

Pesci, A., Bonali, E., Galli, C., Boschi, E., 2011. Laser scanning and digital imaging for the investigation of an ancient building: palazzo dAccursio' study case (Bologna, Italy). J. Cult. Herit. 13 (2), 215–220. https://doi.org/10.1016/j.culher.2011.09.004.

Porras-Amores, C., Mazarrón, F.R., Cañas, I., Villoria Sáez, P., 2019. Terrestial laser scanning digitalization in underground constructions. J. Cult. Herit. 38, 213–330. https://doi.org/10.1016/j.culher.2019.01.007.

Priego, E., Herráez, J., Denia, J.L., Navarro, P., 2022. Technical study for restoration of mural paintings through the transfer of a photographic image to the vault of a church. J. Cult. Herit. 58, 112–121. https://doi.org/10.1016/j.culher.2022.09.023.

Rakhimol, V., Maheswari, P.M.U., 2022. Restoration of ancient temple murals using cGan and PConv networks. Comput. Graph. 109, 100–110, 10/1016/j.cag.2022.11.001.

Regidor, J.L., Roig, P., Abad, Gomez, J., 2007. Pictorical Restoration of Frescos by Transferring Inkjet Prints the Case of Palominos' Frescos in the Church of Santos Juanes in Valencia, Arché 2.

Regidor, J.L., Delhom, S., Valcárcel, J., Zalbieda, A., Soriano, P., 2008. Transferencia de impresiones Ink-jet, una herramienta para la reconstrucción pictórica de faltantes. Arché 3.

Roig, P., 1990. La iglesia de los Santos Juanes en Valencia: proceso de intervención pictórica 1936-1990, Servicio de publicaciones UPV. ISBN: 8477211205, 9788477211204.

Roig, P., 1994. Aproximación al estudio de la obra de Antonio Palomino, Madrid en el Contexto de lo Hispánico Desde la Época de los Descubrimientos, vol. 2, pp. 1405–1421. ISBN: 84-600-8798-0.

Roig, P., Regidor, J.L., Bosh, L., Marcenac, V., 2020. Estudios previos y propuesta de intervención en las pinturas murales, esculturas y ornamentos de la real Parroquia de los Santos Juanes de Valencia, vol. 101. Archivo de Arte Valenciano, pp. 161–177. ISSN: 0211-5808.

Soriano, M.P., 2005. Los frescos de Palomino en la bóveda de la iglesia de los Santos Juanes de Valencia: estudio y aplicación de un nuevo soporte. Tesis Doctoral.

Tobiasz, A., Markiewicz, J., Lapinski, S., Nikel, J., Kot, P., Muradov, M., 2019. Review of methods for documentation, management and sustainability of cultural heritage. Case study: museum of King Jan IIIs' Palace at Wilanow. Sustainability 11, 7046. https://doi.org/10.3390/su11247046.

Vilceanu, C.B., Herban, I.S., Grecea, C., 2013. A Creating 3D models of heritage objects using photogrammetric image processing. AIP Conf. Proc. https://doi.org/10.1063/1.4825832.

Wei, S., 2014. Research on hierarchical imagen restoration of Chinese painting. In: Proceedings of the 9th International Conference on Computer Science & Education, pp. 663–666. https://doi.org/10.1109/ICCCSE.2014.6926544.

Wu, M., Chang, X., Wang, J., 2023. Fragments inpainting for tomb murals using a dual-attention mechanism GAN with improved generators. Appl. Sci. 13, 3972. https://doi.org/10.3390/app13063972.

Zhabg, R., Taylor, A.C., Charalambides, M.N., Balint, D.S., Young, C.R.T., Barbera, D., Blades, N., 2023. A numerical model for predicting the time for crack initiation in wood panel paintings under low-cycle environmentally induced fatigue. J. Cult. Herit. 61, 23–31. https://doi.org/10.1016/j.culher.2023.02.007.