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PHOTOGRAMMETRIC STATE OF DEGRADATION ASSESSMENT OF DECORATIVE CLADDINGS: THE PLASTERWORK OF THE MAIDENS' COURTYARD (THE ROYAL ALCAZAR OF SEVILLE)

EVALUACIÓN FOTOGRAMÉTRICA DEL ESTADO DE DEGRADACIÓN DE REVESTIMIENTOS DECORATIVOS: LAS YESERIAS DEL PATIO DE LAS DONCELLAS (EL REAL ALCÁZAR DE SEVILLA)

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Highlights:

- The photogrammetric survey demonstrates to be a potential tool in the preventive conservation of ancient plasterworks.
- The high-precision 3D model allows the study and quantification of alterations (e.g. fissures, deformations, and loss of mass or polychromies).
- The virtual model and the analysis performed with CloudCompare software provide fast, accurate and accessible results to experts in the field.

Abstract:

Previous studies and documentation about the state of conservation of architectural or decorative elements are crucial for heritage managers, technicians and researchers to succeed in the maintenance and preservation of the heritage. In this sense, hand tracings, digital drawings, or photographs have traditionally been the methods for alteration and sample mapping. In spite of their effectiveness, these methods have some disadvantages, such as the need for more precision in terms of location, dimensions, quantification and types of alterations. By contrast, high-resolution three-dimensional (3D) models allow us to analyse decorative ancient plasterworks with great precision, offering considerable advantages over traditional tools for heritage documentation. To facilitate stakeholders' work and enhance the quality of data collected, this work proposes the use of photogrammetry as a tool for the documentation of polychromed ancient plasterworks, taking the upper frieze of the access door to the Charles V ceiling room in the Royal Alcazar of Seville as a case of study. Thus, the work methodology applied has shown several advantages over previous methods. On the one hand, it was possible to obtain a 2D planimetry from the 3D model; this is an essential step for those responsible for heritage, especially in reports prior to restoration interventions. On the other hand, the 3D model created enables present alterations identification, the location of fissures and cracks in their three dimensions (opening, length and depth), deformations measurement and control, the quantification of mass or polychrome loss, and the detached elements digital reconstruction. In this way, high-precision digital results are quickly obtained and accessible to all the experts involved in the heritage conservation and maintenance plan.

Keywords: historical plasterwork; heritage conservation; management; alterations; digital photogrammetry

Resumen:

Los estudios previos y la toma de datos que documentan el estado de conservación de los elementos arquitectónicos o decorativos es esencial para los administradores, técnicos e investigadores en el proceso de mantenimiento y preservación del patrimonio. En este sentido, los calcos realizados a mano, dibujos digitales o fotografías han sido tradicionalmente los métodos empleados para la documentación de patologías y muestras. A pesar de su eficacia, dichos métodos presentan algunas desventajas como la falta de precisión en términos de localización, dimensionado, cuantificación y tipos de daños. Por el contrario, los modelos tridimensionales (3D) de alta resolución permiten analizar las yeserías históricas decorativas con una gran precisión, ofreciendo ventajas considerables respecto a los medios tradicionales de documentación del patrimonio. Con el objetivo de facilitar el trabajo a los expertos y mejorar la calidad de la documentación recopilada, este trabajo propone emplear la fotogrametría como herramienta en la documentación de revestimientos en yeso policromado, tomando como modelo de estudio el friso superior de la puerta de acceso al salón del techo de Carlos V en el Real Alcázar de Sevilla. Así, la metodología de trabajo aplicada ha demostrado tener varias ventajas respecto a métodos anteriores. En primer lugar, ha permitido obtener con facilidad una planimetría 2D a partir del modelo 3D; ésta es una herramienta fundamental para los responsables del patrimonio, especialmente, en los informes

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previos a las intervenciones de restauración. Por otra parte, el modelo 3D generado, permite indicar con precisión en el relieve, las coordenadas de los puntos donde se extraen micromuestras para el estudio de materiales presentes, localizar alteraciones presentes, medir y controlar fisuras, grietas y deformaciones en sus tres dimensiones (apertura, longitud y profundidad); además, se hace posible cuantificar la pérdida de masa o de policromías, así como reconstruir digitalmente volúmenes perdidos o lagunas de policromía. De este modo se obtienen de forma rápida resultados digitales de alta precisión y accesibles para todos los expertos implicados en el plan de conservación y mantenimiento del patrimonio.

Palabras clave: yeserías históricas; conservación del patrimonio; gestión; alteraciones; fotogrametría digital

1. Introduction

1.1. State of the art

Drawing is a fundamental tool for the analysis and sustainable conservation of architectural heritage. Without a thorough knowledge of the reality to be preserved or restored, it is not possible to carry out adequate actions for its protection and/or maintenance. Throughout history, architectural heritage documentation techniques have been used with different levels of precision depending on the needs, the available tools and the characteristics of the reality portrayed (i.e. engravings, drawings and sketches, photographs, mappings, digitized or by hand planimetric documentation in 2D and 3D, photogrammetric survey, and laser scanner).

Cultural Heritage is in constant danger, due to the continuous risk of natural disasters, climate change, human intervention, as well as the deterioration inherent in the passage of time (Vital & Sylaiou, 2022). Correct graphic documentation on the architectural heritage increases its probability of survival over time, facilitating reconstruction or allowing virtual or material recreation in the event that the heritage was seriously altered by environmental or accidental causes (Higueras, Calero, & Collado-Montero, 2021). In April 2019, the accidental fire of the Notre Dame Cathedral in Paris highlighted the importance of the existence of accurate and detailed graphic documentation (Penagos et al., 2022; Postma, Poirier-Quinot, Meyer, & Katz, 2016).

Thus, the precise geometric registration of heritage sites is crucial for their correct identification, monitoring, preservation and restoration (Elkhrachy, 2022; Grussenmeyer et al., 2016). The techniques currently on the rise are mainly terrestrial laser scanning (TLS) (Moyano, Justo-Estebaranz, Nieto-Julián, Barrera, & Fernández-Alconchel, 2022; Nieto, Moyano, Rico Delgado, & Antón García, 2016) as well as handheld scanning (Menendez, Somonte, & Escudero, 2021), drones (Rodríguez Elizalde, 2022), mobile mapping systems (Benavides López & Barrera Vera, 2020) and digital photogrammetry (Quintilla Castán & Agustín Hernández, 2022).

In recent years, digital photogrammetry, based on the Structure from Motion algorithm (hereinafter, SfM), has established itself as an ideal technique for registering heritage (Alshawabkeh, El-Khalili, Almasri, Bala'awi, & Al-Massarweh, 2020; Cabrera-Revuelta, Mascort-Albea, Hidalgo-Sánchez, Romero-Hernández, & Canivell, 2021). It is a non-invasive technique, so physical contact with the element under study is not required, which is essential for working on elements with a high degree of protection. The digital photogrammetry technique is characterized by being affordable, with great geometric precision and versatile for the acquisition of geometric data, capable of guaranteeing levels of detail equivalent to other tools that are generally more expensive and bulky, such as a laser scanner (Lauria, Sineo, & Ficarra, 2022). This technique also emphasizes the easy portability, as well as the great quality of its textures, well above those achieved with other instrumentation (Cloet, 2022; Felicísimo & Polo, 2022). Digital photogrammetry has endless potential, countless applications and is becoming increasingly popular. Moreover, photogrammetry is usually an economically accessible technique, with respect to other remote sensing techniques (e.g. 3D scanners) (Ortiz-Sanz, Gil-Docampo, Rego-Sanmartín, Arza-García, & Tucci, 2021), whose metric suitability has been widely validated (González-Jorge, Riveiro, Arias, & Armesto, 2012).

SfM photogrammetry is also suitable for complete registration of high-rise claddings. Although the ideal is to take pictures from a position accessible to the camera, the use of poles and remote controls make it possible to maintain image quality for elements located on the upper levels (Del Pozo et al., 2020). An alternative is the use of Unmanned Aerial Vehicles (UAV) that allow the sweeping of an entire vertical surface, in an automated way (Murtiyoso & Grussenmeyer, 2017). However, the restrictions imposed on the use of UAVs in protected places must be considered, as well as the loss of control in the data collection carried out from this type of device. Thus, photogrammetry is a low-cost and versatile technique that can be adapted to a wide range of situations.

In this context, this work addresses the study of historic plasterwork in order to validate the effectiveness of the SfM algorithm and digitize the decorative element as precisely as possible in order to facilitate conservation and subsequent intervention activities. The advantages and implementations offered by the technique will be studied when approaching on-site inspections and through routine non-destructive tests (NDT) for the maintenance of plasterwork. Likewise, the model obtained facilitates the dissemination of elements of great heritage interest, such as this plasterwork, and will allow the virtual and material reproduction of the models (Ávila Rodríguez, 2019; Norin, Golovina, & Tikhonov, 2019).

The use of new digital tools to recover the visualization or appearance of the architectural, archaeological and museum heritage of historical plasterwork has been revealed in numerous previous investigations, among which those focused on the digitization of architectural heritage embellished with plasterwork stands out.

In the case of the Royal Alcazar of Seville (hereinafter, RAS), the works carried out by Almagro Gorbea and his medieval architecture team stand out, in which the general image of medieval coloured plasterwork is recalled in harmony with the tiled baseboards or the polychromed wood carpentry. These reconstructions were focused on the general representation of the architecture and also in claddings but without analysing the plasterworks in detail (Almagro Gorbea, García Bueno, López Cruz, & Medina Flórez, 2010) (Figs. 1a, 1b).

Figure 1: a) Infographic of the Courtyard of the Maidens, RAS (©https://digibug.ugr.es/handle/10481/21749); b) Infographic of the Royal room of Santo Domingo in Granada, ®Almagro Gorbea; c) Virtual image of a plasterboard section (Rubio Domene, 2010).

In light of all the works that have been published in this area, it is important to point out how virtual reconstruction in plasterwork can be used as a teaching tool to explain in detail how these decorations are executed. In this regard, it is important to draw attention to those made by the restorer in charge of the plasterwork at the Alhambra in Granada. (Rubio Domene, 2010) (Fig. 1c). In recent decades, the use of 3D modelling in plasterworks for the study of muqarnas (Agirbas & Yildiz, 2020; Gámiz Gordo & Ferrer Pérez Blanco, 2019; Garofalo, 2010; Maarouf & Zeid, 2019; Schuldes & Winckler, 2005) and the pavilions of the Courtyard of the Lions in the Alhambra has been addressed in order to analyse the levelling of their plasterwork (Ferrer Pérez Blanco, Gámiz Gordo, & Reinoso Gordo, 2019; Gámiz Gordo, Ferrer Pérez Blanco, & Reinoso Gordo, 2020) and get photogrammetric reconstruction (Karabörk, Karasaka, & Yaldız, 2015). As far as the RAS is concerned the new heritage digitization techniques have made it possible to carry out a virtual visit of the complex, based on data obtained from a terrestrial laser scanner (TLS) (360º Virtual Tour, 2022), and from the reconstruction hypotheses of the different buildings (Almagro Gorbea, 2007), as well as the models of small decorative elements in plaster obtained by photogrammetry (Torres-González et al., 2022).

Among the utilities of heritage digitization, the use of digital models for the virtual reconstruction of polychrome decorative elements stands out. The difficulty of approaching this type of virtual chromatic reconstruction in plasterwork is due to the successive interventions that took place on these decorations (Blasco López, 2011; Coba Peña, Calero Castillo, Collado Montero, Hernández Pablos, & Medina Flórez, 2016). Among them, those studies addressed by Coba-Peña and Torres-González (Coba Peña et al., 2016; Torres-González et al., 2022), where a reconstruction of colour in different historical periods was carried out from the identification of colour layers through instrumental techniques (e.g. x-rays diffraction or energy dispersive x-ray analysis), are outstanding.

The use of these digitalized data for applications related to reverse engineering is added to all the applications already mentioned (Fatuzzo, Sequenzia, & Oliveri, 2016; Sequenzia, Fatuzzo, & Oliveri, 2021). Digital photogrammetric surveys and also the data acquired by the use of handheld scans are so accurate that they permit the recreation and replacement of lost fragments using 3D printing techniques, or the manufacture of moulds to reproduce replicas at different scales (Henriques, Bailão, Rocha, & Costa, 2020; Merchán, Merchán, Salamanca, Pérez, & Nogales, 2019). Thus, this technique is ideal for generating extensive databases of 3D elements which classify existing details in different plasterworks located in different places. Making duplicates of detached plasterworks will be possible in the future thanks to the development of volumetric databases.

The main objective of this work is to obtain a virtual model through the use of SfM photogrammetry to validate the usefulness of the tool in its application to historical plasterwork, as well as to contrast and/or implement the results obtained through organoleptic inspection and NDT. The proposal will be aimed at the information systematization towards rational building maintenance decisions and will allow: (i) to document and identify in detail the geometry of the decoration present in the upper frieze of the access door to the Ceiling Hall of Carlos V (Palace of Pedro I), (ii) carry out virtual reconstructions applicable to works of similar chronology based on bibliographic documentation, work on-site and the subsequent digitization, and (iii) deepen the knowledge of the original appearance of this cladding from the virtual modelling of the historic plasterworks.

As far as this study is concerned, photogrammetry is essential in order not only to document the current state of the plasterworks under study, but also to monitor time through periodic photogrammetric records that show the progress in the deterioration and pathologies that affect a building of cultural interest. On the different models obtained, it is possible to analyse and measure relevant data such as the depths of the carving, the inscriptions, the thicknesses, as well as the lengths of fissures and/or cracks. Additionally, these models can be compared with others of similar geometry to study the possible use of moulds or templates in their manufacture.

1.1 Case of study

The RAS has been a Site of Cultural Interest since 1831 and it was declared, together with the Cathedral and the *Archivo de Indias*, a World Heritage Site by UNESCO in 1987 (UNESCO, 2022). The RAS is a palatine complex whose construction began in the 11th century and continues to the present day, with architectural rehabilitation and restoration interventions, a fact that favours the coexistence of different architectural styles (Almohad, Mudejar, Gothic, Neoclassical, Plateresque). The buildings promoted by the monarch Pedro I stand out in what is now known as the 'Palace of Pedro I' (1356-1366) (hereinafter, Palace) (Almagro Gorbea, 2007). In this construction, the compositional richness and the chromaticism of its plasterwork, tiles or carpentries carved in wood stand out, which make it one of the best examples of Mudejar construction that are preserved in the Iberian Peninsula (Tabales Rodríguez, Alejandre Sánchez, Blasco López, & Vargas Lorenzo, 2017).

Since the 14th century, several interventions have been made to the plasterwork. Among these, the documented whitewashing from the 19th century and repolychromies that do not follow the current conservation guidelines stand out (Blasco López, Alejandre Sánchez, Flores Alés, Villegas-Sánchez, & Freire, 2021; Campos de Alvear, 2020)[1]. However, in recent decades, conservation and emergency interventions have also been carried out for the conservation and preservation of the plasterwork of the Palace (Blasco López, Alejandre Sánchez, Flores Alés, & Cortés Albalá, 2016; Blasco López, Alejandre Sánchez, Flores Alés, & Martín del Río, 2012; Cabrera-Revuelta & Aguilar-camacho, 2022; Calero Castillo, García Bueno, López Cruz, & Medina Flórez, 2016; Coba Peña et al., 2016; Serrano Rodríguez, Alejandre Sánchez, Blasco López, & Torres González, 2022; Torres-González, Alducin-Ochoa, Alejandre Sánchez, Flores-Alés, & Blasco López, 2020; Torres-González, Alejandre Sánchez, Flores Alés, Calero Castillo, & Blasco López, 2021; Torres-González, Rubio-Bellido, Bienvenido-Huertas, Alducin-Ochoa, & Flores-Alés, 2021). Mention should be made of the Preventive Conservation Plan that is currently being developed and addresses, among others, the study of more than 2500m^2 of plasterwork that decorates ceilings, walls, and arches on the ground floor of the Palace of Pedro I (Campos de Alvear, 2018). The digitization of the plasterwork is, therefore, input into a database that will be available to the multidisciplinary team that carries out the maintenance and preventive conservation tasks of the RAS (Rodríguez Rodríguez, 2019). Taking into account that the RAS receives more than one million tourists per year, this plan is essential to alleviate the damage caused by the anthropic factor (Troitiño Vinuesa, Troitió Torralba, Salmerón Escobar, & Pérez de la Torre, 2020).

The Courtyard of the Maidens, one of the most representative spaces of the Palace, houses 30% of the plasterwork on the ground floor of the Palace. These plasterworks are directly exposed to environmental conditions, accelerating their deterioration and being the subject of many restoration interventions throughout the history of the RAS (Marín Fidalgo, 1990; Serrano Rodríguez et al., 2022). An example of its numerous interventions is the whitewashing of its plasterwork documented in various investigations (Cómez Ramos, 1996).

Since the year 2000, the TEP-198 research team from the University of Seville and the HUM-104 group from the University of Granada have been studying the plasterwork of the Courtyard of the Maidens (Almagro Gorbea, García Bueno, López Cruz, & Medina Flórez, 2010; Blasco López et al., 2012, 2021; Bueno García & Medina Flórez, 2004; Calero Castillo, García Bueno, López Cruz, & Medina Flórez, 2017; Coba Peña et al., 2016; Torres-González et al., 2022). Within these investigations, the studies of the plasterwork conserved in the southeast wall of the patio are of great interest, mainly due to the formal characteristics of the main entrance of this wall (Calero Castillo, 2016).

To carry out this work, the plasterworks from the upper frieze of the access to the Carlos V Ceiling Hall, located in the Courtyard of the Maidens of the RAS were taken as an object of study (Fig. 2).

2. Methodology

2.1 Documentation and data acquisition

Initially, written and graphic information, was collected to define the state of knowledge of the object of study. Subsequently, on-site data and measurements were compiled, as well as some representative microsamples. For the diagnosis and evaluation of the historical plasterwork and its polychromes, the method proposed by Torres-González et al. 2021 (Torres-González, Alejandre, Flores-alés, Calero-castillo, & Blasco-lópez, 2021) and the results obtained during the inspections of 2016-2020 have been used (Calero Castillo, 2016).

Once the information regarding the southeast gallery of the Courtyard of the Maidens was compiled and analysed (Calero Castillo et al., 2017; Fernández Aguilera, 2015), the fieldwork was carried out. The data collection, carried out during the 2016 (Calero Castillo, 2016) and 2020 campaigns, involved the registration and documentation of the plasterwork and its polychromies in relation to their situation and general identification, their state of conservation, constructive facts. The data handled for this inspection were prepared according to the criteria used in other works (Torres-González et al., 2022; Torres-González, Alejandre, et al., 2021).

In the on-site inspection performed in 2020, voids were identified by using a percussion technique, fissurometres were used to evaluate and measure fissures and cracks, and a mapping of alterations was drawn to indicate dirty, the presence of biological organisms, and the existence of metal nails to fix the plasterworks. Previous analysis was conducted to determine the solubility of the polychromies by rotation of swab impregnated in distilled water and 11 microsamples were taken to deepen the study by stereoscopic microscopy, optical microscopy and scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX) (Calero Castillo, 2016).

2.2 The generation of the 3D model by photogrammetric survey

For the choice of the geometric data collection technique, aspects such as the location of the element of interest, the space, the lighting, as well as the human and material resources available were studied. The plasterwork under study is located at a high height – between 4.50 m and 5.00 m– with respect to the ground level of the southeast gallery of the Courtyard of the Maidens. For the photogrammetric survey, a scaffold with a limited working space and approximately 50 cm separated from the frieze was used. In this particular case, a technician was required to perform the work and the images were always shot on a platform rather than sticking out from the scaffolding to reduce the chance of falling objects.

In addition to the reasons derived from the workspace in terms of the choice of technique, other reasons were taken into account such as (I) the availability on the market of a diverse range of specialized software and its good quality/price ratio, and (II) the suitability of

[1] Any restoration intervention should comply with the standards and guidelines applicable in this case study: Law 16/85 of the Spanish Historical Heritage, Law 14/2007 of the Historical Heritage of Andalusia, recommendations comprised in the different Restoration Charters and the professional guidelines of E.C.C.O. published in 2002.

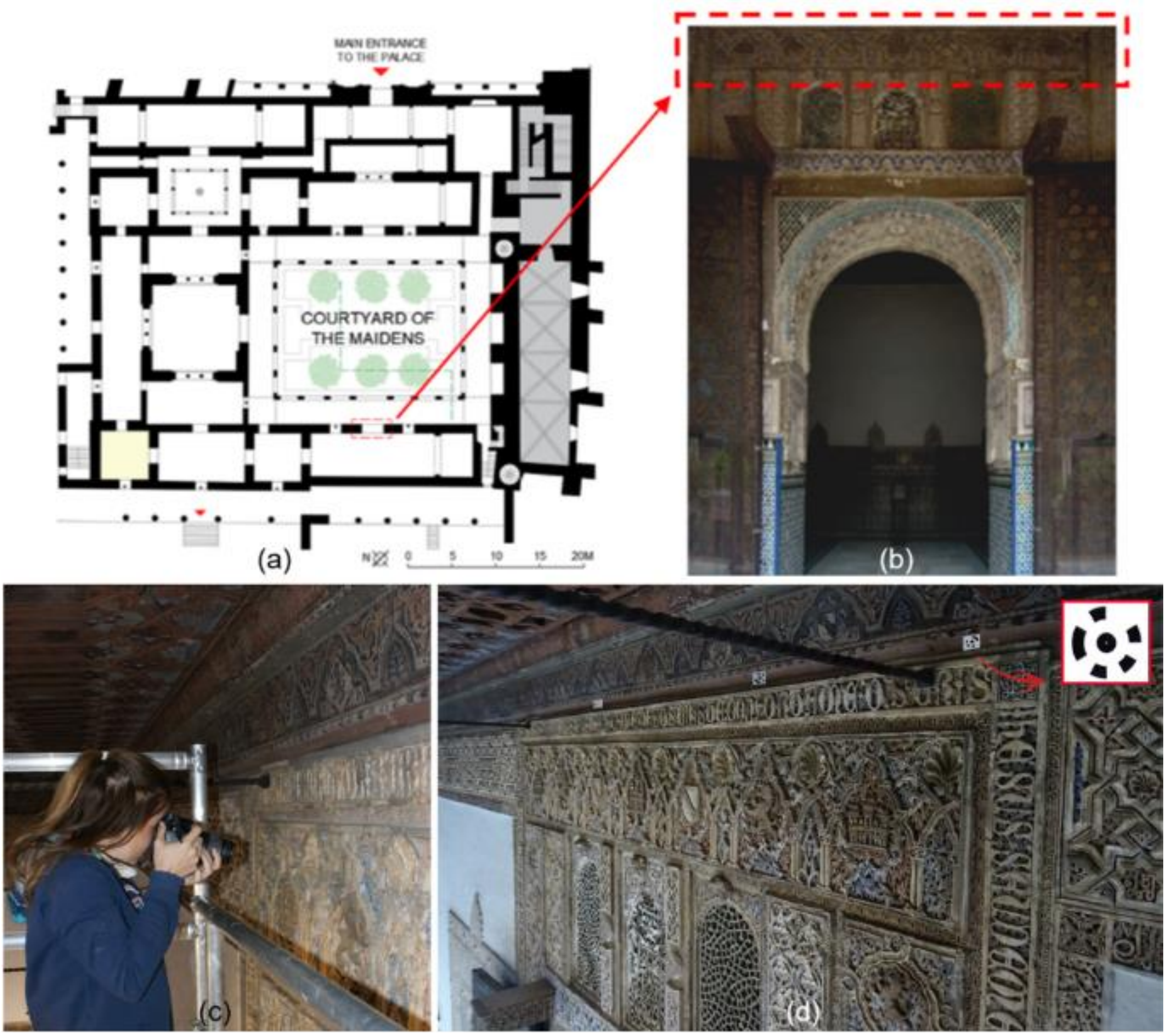

Figure 2: a) Ground floor of the Pedro I Palace (RAS); b) General image of the main entrance to the room of the ceiling of Charles V; c) On-site work; d) Details of the frieze under study and targets used.

the 3D data obtained from an architectural and constructive point of view. Thus, the technique used to create the 3D model can be described according to the following sequence of processes and tools:

- Data collection. In this phase, photographic data were taken, as well as measurements of distances between coded markers that act as reference points, facilitating the post-processing stage. Considering the recommendations provided by Agisoft (Agisoft Metashape, 2022), pictures must be taken with a great overlap. Furthermore, consecutive photographs should have parallel or even convergent axes. The photographic data were taken using a Panasonic LUMIX GX80 camera, with a focal length of 14mm. This camera has a Live MOS sensor of 17.3 x 13 mm. The data collection was carried out by horizontal sweeps at a maximum of 80 cm, obtaining a ground sample distance (GSD) of 0.24 mm. The photographs were taken ensuring an overlap of at least 80%, to allow the software to detect the shapes and geometry of the object to be studied and improve the quality of details and texture. A total of four coded markers were placed on the scene. Due to the high level of protection of the case study, these markers were located around the plasterwork. Six different measures were obtained.
- Post-processing of images. The photographs were imported into the Agisoft Metashape Professional v. 1.8 software to perform a preliminary evaluation of the quality of the images and eliminate those that may generate problems in the alignment process. Subsequently, the necessary masks were made to eliminate undesirable areas of the images. In this case, it was necessary to mask all the protective elements of the scaffolding. After that, the workflow was carried out to obtain a highly accurate point cloud, as well as a textured model. To evaluate the quality of this work, it has been used the metric information from the coded targets. Two of the six distances have been used as control scale bars, and the other four as check scale bars.
- Analysis of the 3D model and/or the point cloud. The files obtained were imported into various software packages for editing and analysis. It is highlighted the use of the CloudCompare v. 2.13. alpha software to compare different models and/or point clouds and to carry out a record of the deformations suffered by the element over time.

3. Results and discussion

This section is divided into two parts based on the photogrammetric survey's direct results (Section 3.1) and those retrieved from the analysis of the 3D model that permits assessing the state of conservation of plasterworks (Section 3.2).

3.1 Photogrammetric survey

In this case, 190 photographs were taken for the realization of the model (Table 1). The dense point cloud achieved is composed of more than 171 million points (Figs. 3 and 4). The textured photogrammetric model was made through the workflow of depth maps, in extra high quality, with more than 18 million faces. The model obtained allows a deep and detailed analysis of the geometry of the variety of plasterworks. It was corroborated that photogrammetry is useful to obtain a high-precision model, allowing the identification of cracks and fissures, and the measurement of thicknesses and depths. On the other hand, the point cloud obtained had a level of detail of 0.25 mm. The model was performed in the highest quality, obtaining a mesh with a level of detail of 1 mm. According to the report provided by the software, the control scale bars error was 0.19 mm, while the check scale bars error was 0.32 mm.

In addition to the point cloud and the textured photogrammetric model, the orthophoto of the complete plasterwork was obtained (Fig. 5).

Table 1: Photogrammetric model data.

Triangles	18.3 million
Vertices	9.18 million
Software	Agisoft Metashape Pro
Instrument	Panasonic DMC-GX80 camera(14mm)
Marks	12 bits encoded marks (x4)
Error	0.32 mm

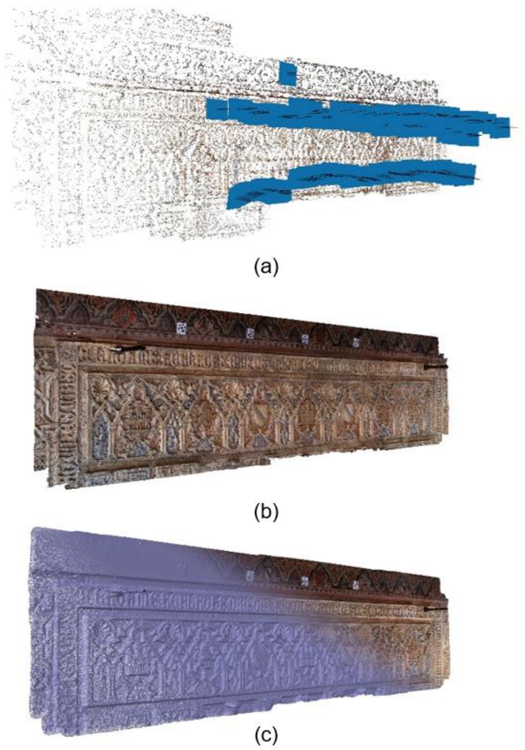

Figure 3: Data processing in Agisoft Metashape©: a) sparse point cloud showing camera positions; b) dense point cloud; c) composition of the model.

Figure 4: Detail of the model obtained showing wired, solid and textured structure.

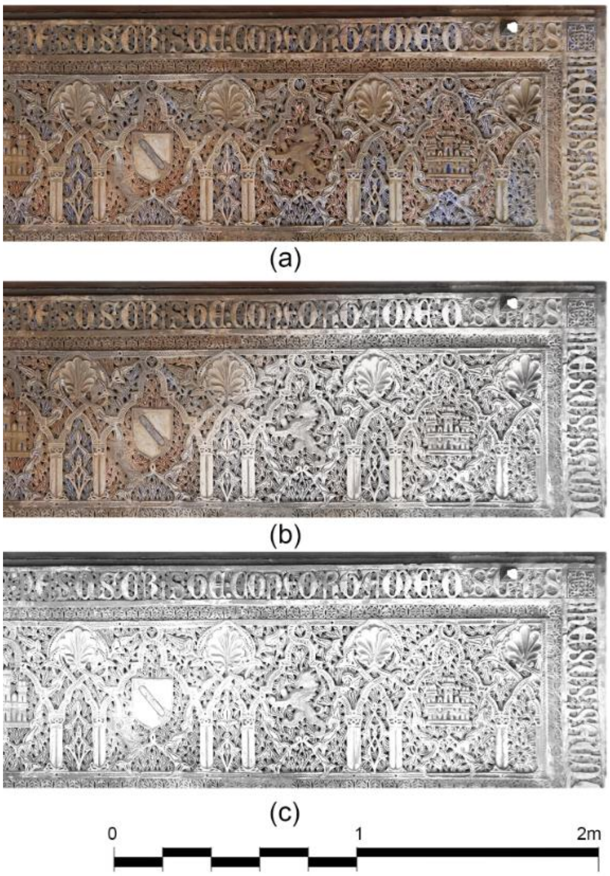

Figure 5: Process followed to obtain the photogrammetric survey: a) orthophoto of the decorative frieze; b) b&w image editing process; c) final conversion into drawing in Adobe Photoshop CS6.

3.2. Conservation state of the plasterworks

The study of the alterations of the historical plasterwork is essential when it comes to knowing and preventing the causes of alteration and intervening in its restoration, maintenance and conservation (Cotrim, Veiga, & De Brito, 2007; Historic Environment Scotland, 2016). If the alterations or damages are very serious, and they are not detected and cleaned up in time, the plasterwork –and, in general, the rocks– can lose their mechanical resistance functions, due to progressive loss of cohesion or reduction of its mass.

3.1.1. Sizing and monitoring of cracks & fissures

The orthophoto obtained from the photogrammetric model allowed the elaboration of a digital mapping of damages (Fig. 6) where the fissures and cracks identified during the photogrammetric survey on-site were located. As an example, Fig. 7 shows a 15.1 cm in length crack.

In this regard, the main advantage of the digital model is the possibility of monitoring cracks and crevices over time by overlapping point clouds. Thus, a quantitative study in terms of length, aperture and depth, without the need for auxiliary means (i.e. placement of plaster cores) is possible.

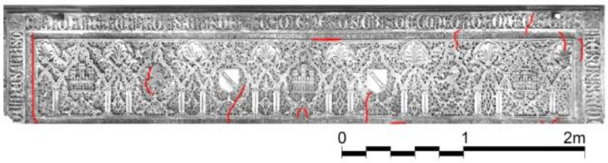

Figure 6: Mapping of cracks and fissures on a 2D plane.

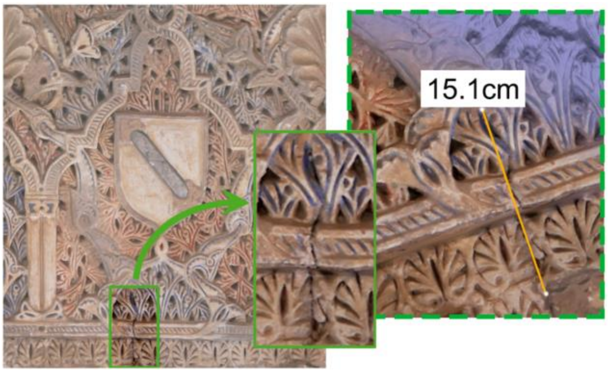

Figure 7: Information on fissures and cracks identified in the photogrammetric model.

3.1.2. Loss of polychromies and detachments of the plasterwork

Until now, surface calculations with colour gaps have been performed manually by identifying the affected areas over 2D drawings or plans. This method yields quite reliable approximate results at the 2D level, but it is not recommended in the case of plasterwork with relief since the surface to be repolychromed does not coincide with the surface represented in a 2D plane. The photogrammetric model allows us to select the areas without polychromy and offers the surface taking into account the relief of the decorations, providing numerical data that is more accurate than that acquired by conventional methods. In addition, it is possible to filter points by colour from the dense point cloud, to obtain the surface painted with a specific polychromy. By contrast, it is also possible to detect places where the polychromy has been detached (Figure 8).

Similarly, it is possible to quantify detached areas or volumes with sub-millimetre precision by using the photogrammetric model, thus surpassing traditional measurement techniques (Figure 9).

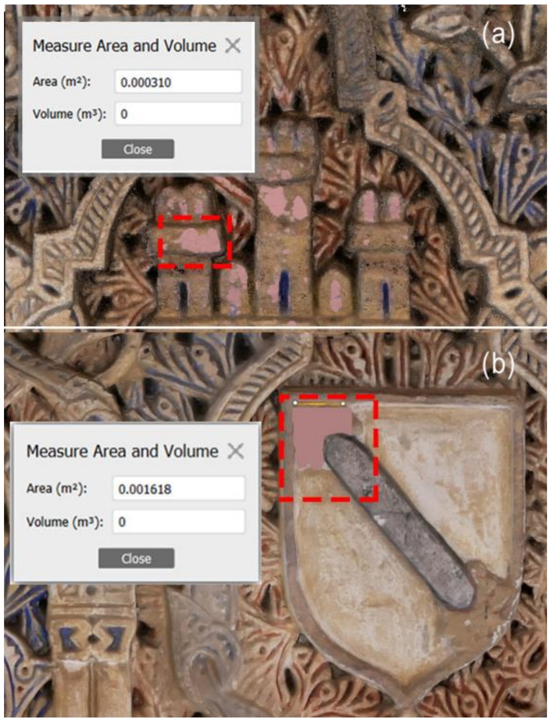

Figure 8: Measurement in Agisoft Metashape Pro of: a) colour gaps and b) detached fragments.

3.1.3. Model deformations

During on-site inspections, it is very difficult to appreciate the deformations unless they are very striking, since the experts need auxiliary means, adequate lighting and accessibility conditions of the whole to be able to issue an accurate diagnosis (e.g. plasterwork located at 4.5 m high, accessible thanks to a scaffolding located at a short distance and poor natural lighting is not the most favourable situation to study deformations).

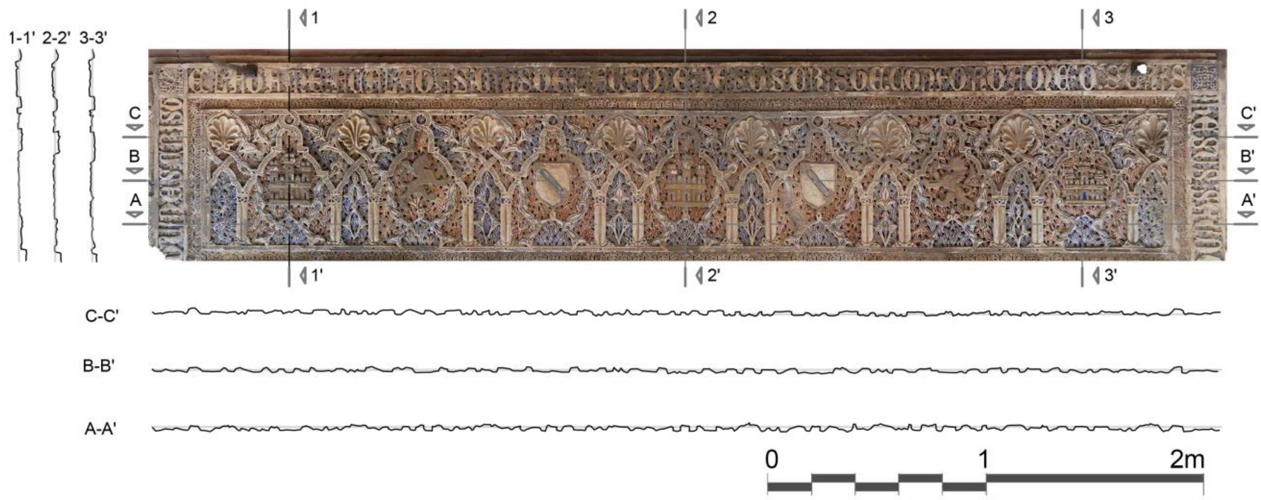

Figure 9: Horizontal (A-A’, B-B’, C-C’) and vertical profiles (1-1’, 2-2’, 3-3’) of the frieze under study.

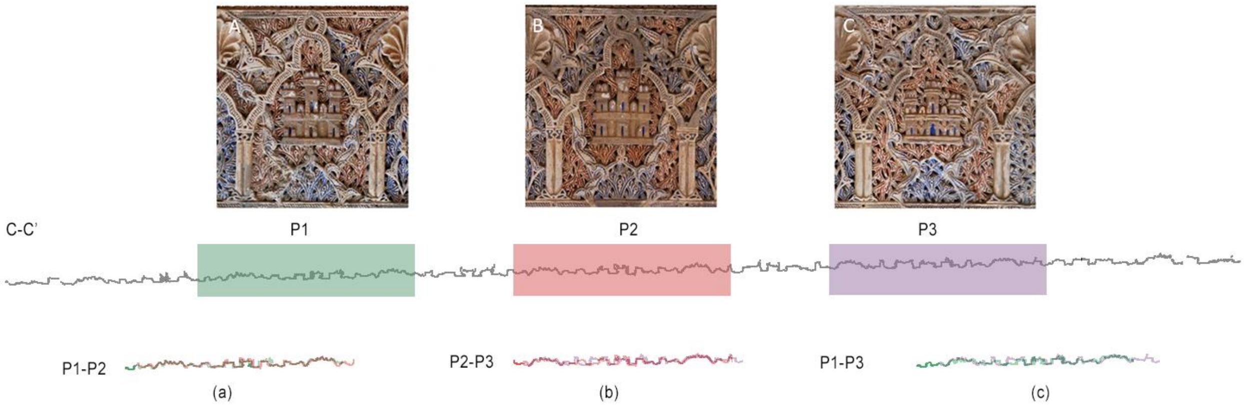

Figure 10: Deformations of the photogrammetric model in the horizontal profile C-C': a) overlapping of P1 & P2 profiles, b) overlapping of P2 & P3 profiles; c) overlapping of P1 & P3 profiles.

From the photogrammetric model obtained, the deformations of the plaster frieze were analysed. To do this, a series of sections have been executed using the dense point cloud. Vertical sections 1-1', 2-2' and 3-3' and horizontal sections A-A', B-B' and C-C' (Fig. 9). These sections allowed analysing of the similarities in the profile of three parts of the plasterwork of similar geometric composition (Fig. 10).

First, the differences between verticality and the union of the ends in sections 1-1', 2-2' and 3-3' were analysed. These sections are slightly inclined forward at the top, resulting in angles of 1.565°, 1.373° and 1.144°, respectively. This means that the verticality of the frieze is variable along it, being more vertical as we move to the right. On the other hand, sections A-A', B-B' and C-C' were joined to analyse their profiles. In this case, the sections are predominantly maintained frontal, differentiating angles of 0.135°, 0.122° and 0.115°, respectively.

In addition, it was possible to analyse the geometric similarities of the sections made on parts of a similar geometric composition (e.g. the three castles carved on the plasterworks). The overlaps of their profiles revealed a great geometric coincidence between certain specific parts of the plasterwork. Therefore, it can be said that the graphic documentation obtained from photogrammetry offers an unprecedented amount of data for a complete analysis and study.

Likewise, the superposition of the point clouds of the different carved decorative motifs can yield information regarding the deformations or in terms of the geometric differences detected in the carving of the plasterwork. Figure 11 shows two different comparisons made on two parts with similar geometric compositions. On the one hand, the Cloud-to-Cloud distance comparison (C2C) in Cloud Compare (Fig. 11a) shows the absolute distances between two clouds. In this comparison the mean value obtained was 2.28 mm, and the standard deviation was 2.41 mm. On the other hand, the Cloud-to-Mesh distance comparison (C2M) (Fig. 11b) shows the distance between two meshes. In this case, the mean value obtained was -0.65 mm, while the standard deviation was 2.9 mm.

In this case, there are no major deformations, but the differences in carving, not noticeable by the human eye, were highlighted.

This kind of analysis permits not only to take measurements of deformations in the current status or by comparing different areas of the dense cloud points, but also measurements in long-term monitoring by overlapping the dense cloud points of an specific area years after this work. By doing that, the evolution of deformations over time could be studied obtaining high-precision measurements that would help stakeholders in the management of the RAS.

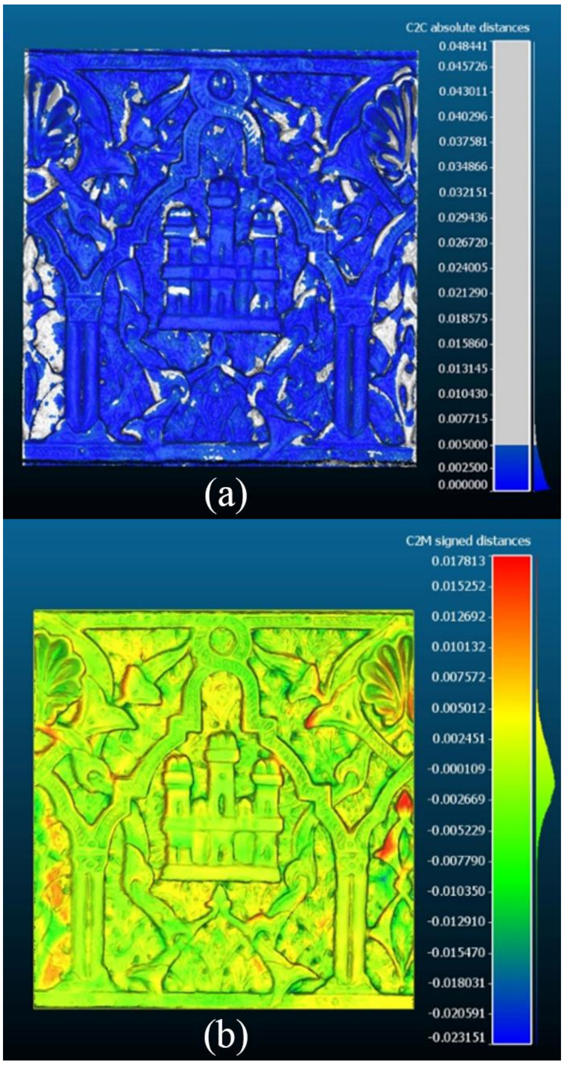

Figure 11: Comparison of distances in Cloud Compare. a) C2C comparison; b) C2M comparison.

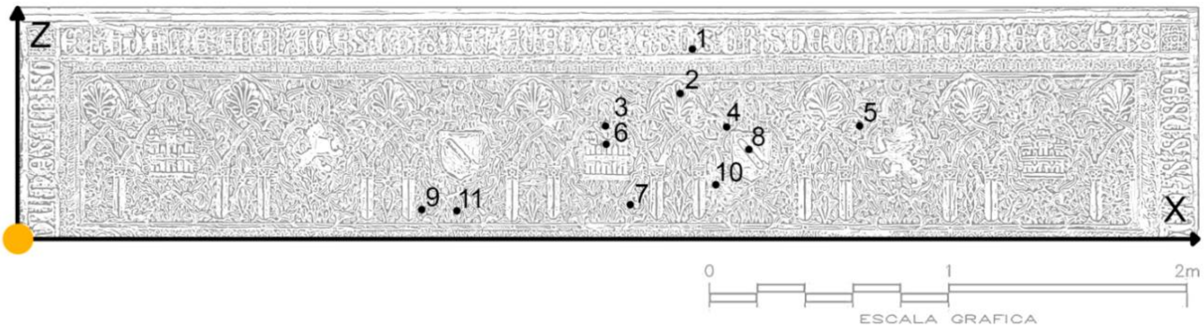

Figure 12: Location of the polychrome samples analyzed.

3.1.4. Sampling records

Another advantage of photogrammetry is the precision to record the coordinates (X,Y,Z) of the microsample extraction point by favoring the rapid location of the microsample in the 3D digital model. Thus, the error induced by traditional means is removed and replaced by a high-precision location of specific points or areas.

Taking point 0 as the origin of the coordinate system, and establishing the coordinate system (X, Y, Z) –(distance, depth and height) as shown in Fig. 12–, the exact location of the sampling carried out was obtained (Table 2).

Table 2: Information on polychrome samples obtained.

Samples Id.	*Designation*	*Point coordinates (X,Y,Z) extracted from 3D model (m)*
1	Artificial ultramarine mixed with azurite	(2.561, 0.122, 0.742)
2	Iron oxide yellow, lead white, barite and calcite	(2.503, 0.116, 0.582)
3	Gold over lead red base, cinnabar/vermilion	(2.205, 0.078, 0.432)
4	Artificial ultramarine	(2.708, 0.084, 0.404)
5	Iron oxide yellow	(3.247, 0.117, 0.429)
6	Gold over lead and chrome yellow base; over lead red and cinnabar/vermilion	(2.210, 0.069, 0.339)
7	Red earth over red lead, cinnabar/vermillion	(2.344, 0.068, 0.114)
8	Black (pigment mix)	(2.814, 0.075, 0.310)
9	Red land	(1.438, 0.047, 0.087)
10	Natural red on lead red, cinnabar/vermillion	(2.669, 0.071, 0.181)
11	Natural yellow over ultramarine	(1.581, 0.038, 0.065)

The preliminary analysis of the polychromes indicated that most of them are unstable and powdery -except for the black pigments that punctually decorate the plasterwork and the sheets of gilding that have a better fixation than the rest because they are modern repolychromed laying down a special medium to improve the adhesion of the gold leaf . Eleven microsamples taken were observed under the microscope and analyzed by SEM-EDX (Calero Castillo, 2016).

Figure 13 shows an example of information obtained from this analysis, corresponding to the sample identified as number 6. The presence of chlorine is indicative of air pollution; mixture of lead red and cinnabar/vermilion and remains of earth; leveling layer with white lead, calcium carbonate and some grains of lead red (silica, chromium are contaminations); layer of preparation for the application of gold; gold, small amounts of Cu and Ag.

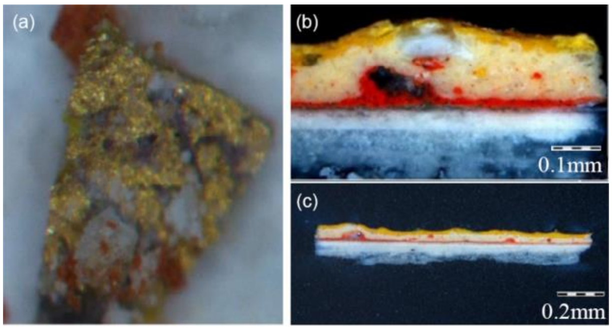

Figure 13: Images of sample 6: a) optical microscopy; b) and c) stratigraphy.

3.1.5. Volumetric reconstructions and polychrome reconstructions

Finally, the high-precision photogrammetric 3D model allows the post-processing of the point cloud and/or textures and volumetric reconstructions can be performed by isolating details and exporting the elements to third-party modelling software.

In this way, not only would it be possible to undertake an intervention to rebuild detached fragments, but the necessary counter molds could be generated to replicate these decorations (Fig. 14). In fact, the reconstruction of plasterwork using digital tools and modern techniques such as computerized numerical control milling (CNC milling) and laser cutting (Marshall, 2007) or scanning and reproduction by 3D printing in polylactic acid (PLA) is currently being promoted (Ávila Rodríguez, 2019; Norin et al., 2019). Likewise, it would also be possible to hypothesize the original polychromies or polychromies that can be applied in future restoration interventions to validate the intervention (Torres-González et al., 2022).

According to other photogrammetric works in the field of architectural heritage (Caro and Hansen, 2015; Alshawabkeh, El-Khalili, Almasri, Bala'awi, & Al-Massarweh, 2020; Reinoso, Gámiz, Barrero, 2021),

(a) (b) (c)

Figure 14: Working process with the volume corresponding to the castle: a) photogrammetric 3D mesh; b) isolated detail of the photogrammetric 3D mesh; c) reconstruction of the polychromy according to samples 3 and 6.

the technique demonstrated to be useful and precise in relation to plasterworks decorations. However, it should be noted that, in comparison with other types of decorations (e.g. canvas, wall paintings, etc.) (Calero-Castillo et al., 2020), the repetition of motifs in the plasterwork can make it challenging to obtain both the photogrammetric model and their subsequent processing. For this reason, it is necessary to work with correctly identified targets during data collection and do a thorough job during the treatment of the generated documentation.

Compared to the traditional documentation systems of medieval plasterwork in 2D (Calero-Castillo, 2016), the application of photogrammetry for the documentation of plasterwork presents itself as a considerable advance by obtaining 3D models of great precision, something that was not possible in the past.

One of the main advantages provided by this method is the possibility of comparing the evolution of the degradation of decorations in 3D, which is essential in this type of element. However, it should be noted that great technical knowledge and professional computer equipment are required to obtain reliable and guaranteed results, which allow the visualisation of fine material details and features.

4. Conclusions

Photogrammetry proved to be a high-precision potential tool for surveying the Palace of Pedro I (RAS) historical plasterworks in the following aspects:

- Dissemination of models and geometries of great historical-artistic value that had not been documented to date with a high level of precision. The graphic analysis provided by this research contributed to a sustainable conservation approach towards the plasterwork. Similarly, this work is expected to contribute to the consolidation of the historical plasterwork significance as an outstanding identity symbol of this Mudejar Palace in the RAS.
- Quantification of the alterations detected. In this work, fissures and cracks were studied, and no significant alterations were identified in the frieze.
- Quantification of loss of mass and/or polychromies in terms of surface and volume.
- Deformations were studied throughout horizontal and vertical sections, and the reliefs of different areas were compared. A deeper analysis should be carried out to conclude the use of templates or moulds for the fabrication of these artefacts.
- Identification with 3D coordinates of the location of the microsamples studied. It is replicable to other facts, such as the position of alterations detected in the digital model.
- Reconstructions of the original designs, distorted over time, and of the polychrome finishes in the different eras were guaranteed.

It should be remarkable that this work based on a photogrammetric survey generates results quickly, accurately and accessible because the digital file can be consulted in the near future, whenever experts need to address a specific study. Photogrammetry has made it possible to obtain a large amount of data in a short period of time, significantly optimizing data collection with respect to other systems, such as in-situ damage mapping.

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