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Lux in Tenebris: a workflow for digitizing and visualizing pictorial artworks in complex museum contexts

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ABSTRACT

In museum contexts, it is common to meet logistical limitations that make it difficult to document artworks. The pictorial heritage introduces further challenges due to the non-modifiability of the lighting setup, which is based on preservation and communication criteria that emphasize the material and execution characteristics of the artwork. This can result in situations that are unsuitable for conducting surveys based on photographic images, which are already complicated by the optical properties of areas covered in gold leaf. The data processing technique described here was developed for the documentation of the Annunciation (1430-32) by Fra Giovanni Angelico (Museo Basilica S. Maria delle Grazie, San Giovanni Valdarno, Arezzo) and it offers the elimination and mitigation of undesirable phenomena due to the specific conditions of the museum context. A strategy capable of removing shadows and chiaroscuro effect from the textures associated with the digital model of the painting and its frame is presented, ensuring its visual reliability.

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LUX IN TENEBRIS: UN FLUJO DE TRABAJO PARA DIGITALIZAR Y VISUALIZAR OBRAS DE ARTE PICTÓRICAS EN CONTEXTOS MUSEÍSTICOS COMPLEJOS

LUX IN TENEBRIS: A WORKFLOW FOR DIGITIZING AND VISUALIZING PICTORIAL ARTWORKS IN COMPLEX MUSEUM CONTEXTS

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En el ámbito museístico es frecuente encontrarse con limitaciones logísticas que dificultan la documentación de las obras de arte. El patrimonio pictórico presenta además otras dificultades debidas a la imposibilidad de modificar la iluminación basada en criterios de conservación y comunicación, haciendo resaltar las características materiales, cromáticas y de ejecución. Esto conduce a situaciones inadecuadas para el levantamiento a través de imágenes fotográficas, ya complicadas en sí por las complejas propiedades reflectivas de los materiales. La técnica que aquí se presenta fue desarrollada para la documentación de la Anunciación (1430-32) de Fra Giovanni Angelico (Museo de la Basílica S. Maria delle Grazie, San Giovanni Valdarno, Arezzo) y permite eliminar y atenuar fenómenos indeseables debidos a las condiciones específicas del contexto museístico. Se mostrará una estrategia capaz de eliminar las sombras nítidas, así como los fenómenos de claroscuro, de las texturas asociadas al modelo digital de la pintura y su marco, garantizando su fidelidad visual.

PALABRAS CLAVE: FRA ANGELICO, MUSEOS, FOTOGRAFÍA, RENDERIZADO EN TIEMPO REAL, ELIMINACIÓN DE SOMBRAS

In museum contexts, it is common to meet logistical limitations that make it difficult to document artworks. The pictorial heritage introduces further challenges due to the non-modifiability of the lighting setup, which is based on preservation and communication criteria that emphasize the material and execution characteristics of the artwork.
This can result in situations that are unsuitable for conducting surveys based on photographic images, which are already complicated by the optical properties of areas covered in gold leaf. The data processing technique described here was developed for the documentation of the Annunciation (1430-32) by Fra Giovanni Angelico (Museo Basilica S. Maria delle Grazie, San Giovanni Valdarno, Arezzo) and it offers the elimination and mitigation of undesirable phenomena due to the specific conditions of the museum context. A strategy capable of removing shadows and chiaroscuro effect from the textures associated with the digital model of the painting and its frame is presented, ensuring its visual reliability.

KEYWORDS: FRA ANGELICO, MUSEUMS, PHOTOGRAPHY, REAL-TIME RENDERING, SHADOW REMOVAL

Introducción

En la documentación del patrimonio pictórico, existen una serie de dificultades “estructurales” con respecto al tema de la digitalización, atribuibles a la coexistencia de materiales “difíciles”, así como a soluciones de iluminación artificial complejas y no variables, que generalmente complican el levantamiento de las pinturas. Las sombras nítidas, los claroscuros marcados y la alta especularidad de las superficies son fenómenos ópticos muy comunes presentes en las obras expuestas en instalaciones permanentes, así como en exposiciones temporales.

Estos efectos, en parte intrínsecos, en parte debidos al contexto, influyen en la percepción de las obras según criterios de exposición, pero al mismo tiempo pueden condicionar y interferir en las operaciones de documentación digital que se realizan cada vez más durante las exposiciones por motivos de conservación, estudio **1** y seguros.

Dentro de este campo especializado de la adquisición 3D mediante imágenes fotográficas, una tarea muy compleja es la de las pinturas más antiguas, que se caracterizan por la copresencia de pigmentos, con un comportamiento especular propio de los materiales dieléctricos, y superficies adornadas con pan de oro, que reflejan la luz con las propiedades anisotrópicas típicas de los materiales metálicos.

A esto se añade el hecho de que los relieves de los marcos generan sombras propias y arrojadas indeseables, que aparecen en los detalles estilísticos clásicos que embellecen y caracterizan las cornisas con medias columnas, pilastras estriadas y capiteles junto con elementos fitomórficos.

El resultado del levantamiento con técnicas fotográficas, a falta de estrategias adecuadas para tratar estos problemas e independientemente de la precisión morfológica, se caracteriza por texturas de color aparente muy alejadas del albedo (es decir, color “puro” no afectado por las sombras), por claroscuros y dominantes de color debidos a la interacción con el entorno, y por la dificultad de reproducir los efectos de reflexión especular y de transmisión.

Una vez que se desea volver a iluminar digitalmente tales artefactos digitales 3D se produce el llamado “efecto de doble sombra”. En la práctica, las sombras ya presentes en la textura de color difuso se sumarán a las calculadas por el renderizado, produciendo un oscurecimiento poco natural de las zonas ocluidas por los rayos de luz, o una falta de coherencia con la proyección de sombras generada por el nuevo juego de luces (virtuales).

Como es bien sabido, la ley que regula la intensidad de la luz, o irradiancia, se basa en la ley de la inversa del cuadrado de la distancia a la fuente emisora de la radiación luminosa. Este fenómeno puede considerarse despreciable en situaciones como exteriores iluminados por la luz solar, pero adquiere gran relevancia en interiores iluminados artificialmente con la intención de enfatizar reflejos, volúmenes y microdetalles de una obra pictórica: el decaimiento de la intensidad luminosa es evidente, generando además de las sombras nítidas gradientes de iluminación de compleja gestión.

El ámbito de la investigación que aquí se presenta se refiere, por tanto, a los criterios y métodos con los que crear contenidos 3D “basados en la realidad” de obras pictóricas inmóviles con el “agravante” de

Introduction

In the documentation of the pictorial heritage, there are several ‘structural’ challenges related to digitization, due to the presence of ‘difficult’ materials and complex, non-adjustable artificial lighting solutions that make it difficult to digitize paintings accurately. Hard shadows, pronounced *chiaroscuro*, and high specularity of surfaces are common optical phenomena in both permanent installations and temporary exhibitions.

These effects, which are partly inherent and partly due to the context, influence the perception of the works according to specific exhibition criteria. However, they can also affect and interfere with digital documentation operations, which are increasingly carried out for conservation, study **1**, and insurance purposes, also during exhibitions. In the specialized field of 3D acquisition through photographic image-based solutions, the digitization of ancient paintings is particularly challenging, due to the coexistence of pigments (which behave like specular dielectric materials) and surfaces embellished with gold leaf (presenting an anisotropic specularity typical of metal conductors).

Furthermore, the survey of frames is often affected by their own shadows, with undesirable artifacts that are present in the structure of classical stylistic elements such as semi-columns, fluted pilasters, capitals, and phytomorphic elements. The outcome of detecting 3D digital artifacts through photographic techniques, in the absence of appropriate strategies to manage these issues and regardless of morphological accuracy, is characterized by textures with apparent colors that are far from the albedo (i.e., the ‘pure’ color unaffected by shadows), *chiaroscuro*, “color bleeding” due to interaction with the environment, and the difficulty of reproducing the effects of specular reflections and transmission. When attempting to digitally re-illuminate such 3D digital artifacts, a phenomenon called the ‘double shadow effect’ occurs. In practice, the shadows already present in the texture of the diffuse color will be added to those calculated by rendering, resulting in an unnatural darkening of the areas occluded to light rays, or a lack of coherence with

1. El modelo tridimensional de la Anunciación, visto en Real-Time Rendering en la aplicación desarrollada específicamente para permitir la exploración del artefacto digital

1. The three-dimensional model of the *Annunciation*, as displayed in Real-Time Rendering in the application specifically developed to allow the exploration of the digital artefact

the projection of shadows generated by the new set of (virtual) lights.
As is known, the law that governs luminous intensity, or irradiance, is based on the inverse square law of the distance from the emission source of the luminous radiation. This phenomenon can be considered negligible in situations such as exteriors lit by sunlight, but it becomes extremely relevant in contexts of artificially lit interiors with the intent to emphasize reflections, volumes, and micro-details of a painting: the decay of light intensity clearly appears, generating complex lighting gradients as well as sharp shadows. The aim of the research presented here, therefore, concerns the criteria and methods to create reality-based 3D assets of immovable paintings that present the problems exposed with the 'burden' of unchangeable lighting. The goal is the generation of models, and the relative set of textures, elaborated in such a way as to document the smallest perceivable detail through photographic and photogrammetric solutions.
This is a problem to which various types of solutions have been proposed, from the manipulation of the single acquired images **2**, to the subsequent correction of the texture obtained by mixing the various shots based on the (*u,v*) reference of the polygonal model **3**. These solutions were experimented leading to alternating results, time-consuming, but which in general demonstrated their inadequacy with respect to the need for an accurate determination of the decay of light on complex surfaces.
There are many reasons for this, but the main is certainly due to the discrepancy or lack of coherence between the perceived image of the three-dimensional object and its segmented multi-projection into the parametric (*u,v*) space, which usually occurs based on geometric optimization criteria due to the mean values of the normals in the polygonal model.
In this context, this paper, through the proposed method, aims to provide a global and automated procedure to globally treat the diffuse component of light on a texture obtained through automatic parameterization **4**. The occasion was provided by the exhibition "Masaccio and Angelico. Dialogue on truth in painting **5**", in which a research

una iluminación inalterable. El objetivo es la generación de modelos, y del conjunto de texturas asociado, procesados de forma que se documente hasta el más mínimo detalle perceptible mediante soluciones fotográficas y fotogramétricas.

Se trata de un problema para el que se han propuesto varios tipos de soluciones, que van desde la manipulación de cada una de las imágenes adquiridas **2** hasta la corrección a posteriori de la textura obtenida mezclando las distintas tomas en función de la referencia (*u,v*) del modelo poligonal **3**.

Estas soluciones han sido objeto de experimentos que han conducido a resultados variables, más o menos laboriosos, pero que en general han demostrado su inadecuación con respecto a la necesidad de determinar con precisión la disminución de la luz en superficies complejas.

Las razones son múltiples, pero la principal se debe sin duda a la discrepancia o falta de coherencia entre la imagen percibida del objeto tridimensional y su transposición al espacio paramétrico (*u,v*), que suele tener lugar en base a criterios de optimización geométrica debido a la tendencia media de las normales del modelo poligonal.

En este contexto, el presente trabajo, a través del método propuesto, pretende proporcionar una metodología global y automatizada para tratar de forma global la componente difusa de la luz sobre una textura obtenida por parametrización automática **4**.

La ocasión la brindó la exposición "*Masaccio y Angelico. Diálogo sobre la verdad en la pintura* **5**", en la que un grupo de investigación del Departamento de Arquitectura de la Universidad de Bolonia realizó la digitalización de la *Annunciazione* (1430-32) que hoy se conserva en el Museo de la Basílica de Santa Maria delle Grazie, en San Giovanni Valdarno, una de las tres Anunciaciones que pintó Guido di Pietro da Mugello, más conocido como Fra Angelico, y de las que las otras dos se encuentran una en el Museo del Prado de Madrid y otra en el Museo Diocesano de Cortona.

La *Annunciazione* de San Giovanni Valdarno consiste en un cuadro de 1950×1580 mm rodeado de un marco de madera dorada, que incluye un redondel en la parte superior con la imagen del profeta Isaías y una predela en la base, en la que se representan cinco escenas de la vida de la Virgen **6**.

El cuadro principal, que representa al arcángel Gabriel en el acto de anunciar a la Virgen la inminente maternidad divina, es un complejo conjunto de simbolismo mariano, representado con colores saturados y atractivos, como el rojo del manto angélico o el azul lapislázuli del manto de la Virgen.

Sin embargo, es la magnífica decoración en pan de oro, dedicada a los detalles de los ropajes y las auras de las figuras, la que cataliza la atención del observador, proyectado en una historia donde la luz, así como el color resultante, se convierten en protagonistas.

El sistema desarrollado para visualizar digitalmente la obra maestra de Angelico, denominado *AnnunciatiONapp*, presta especial atención a la definición de su modelo 3D, a la visualización de materiales complejos, como el pan de oro que la caracteriza, y a la eliminación de las sombras debidas a las condiciones lumínicas de adquisición (Fig. 1).

1

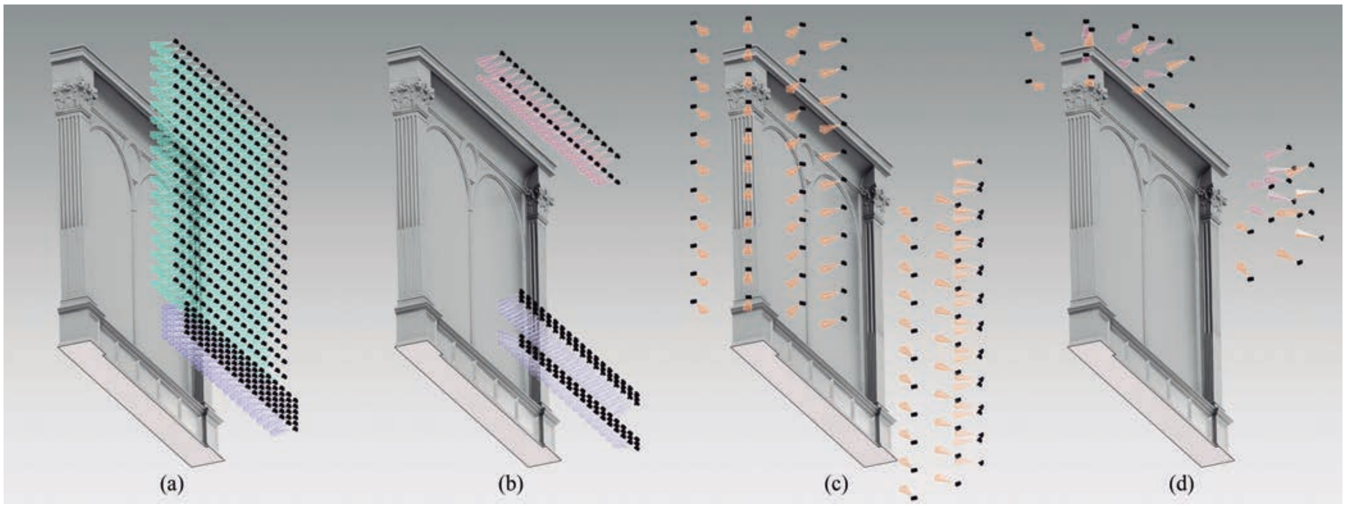
Construcción de un modelo digital tridimensional del cuadro y su entorno

La adquisición y construcción del modelo 3D de la *Annunciazione* se realizó utilizando únicamente técnicas fotográficas y fue el resultado de la integración de las dos soluciones más comunes utilizadas para digitalizar pinturas **7**:

- Imágenes de gigapíxeles, precisas en resolución de imagen, pero limitadas a una mera reproducción del color aparente, y sin ninguna capacidad para mostrar la tridimensionalidad de la pintura y sus propiedades de reflectancia (CABEZOS-BERNAL, RODRIGUEZ-NAVARRO y GIL-PIQUERAS, 2021);
- Modelos 3D basados en fotogrametría automática, precisos en la reproducción métrica y de características 3D, pero generalmente no en la reproducción del color y, en cualquier caso, incapaces de reproducir la mayoría de las propiedades de reflectancia (REMONDINO et al., 2011).

A ellas se añadió una tercera tecnología, la estereoscópica fo-

group from the Department of Architecture at the University of Bologna carried out the digitization of the Annunciation (1430-32), now exhibited at the Museum of the Basilica of Santa Maria delle Grazie, in San Giovanni Valdarno. It is one of the three Annunciations that Guido di Pietro da Mugello, better known as Fra Angelico, painted while the other two are at the Prado Museum in Madrid and at the Diocesan Museum in Cortona.
The Annunciation in San Giovanni Valdarno is composed of a painting measuring 1950×1580 mm surrounded by a gilded wooden frame, including a *tondo* at the top with the image of the Prophet Isaiah and a *predella* at the base, depicting five scenes from the life of the Virgin **6**. The main painting, which depicts the Archangel Gabriel in the act of announcing



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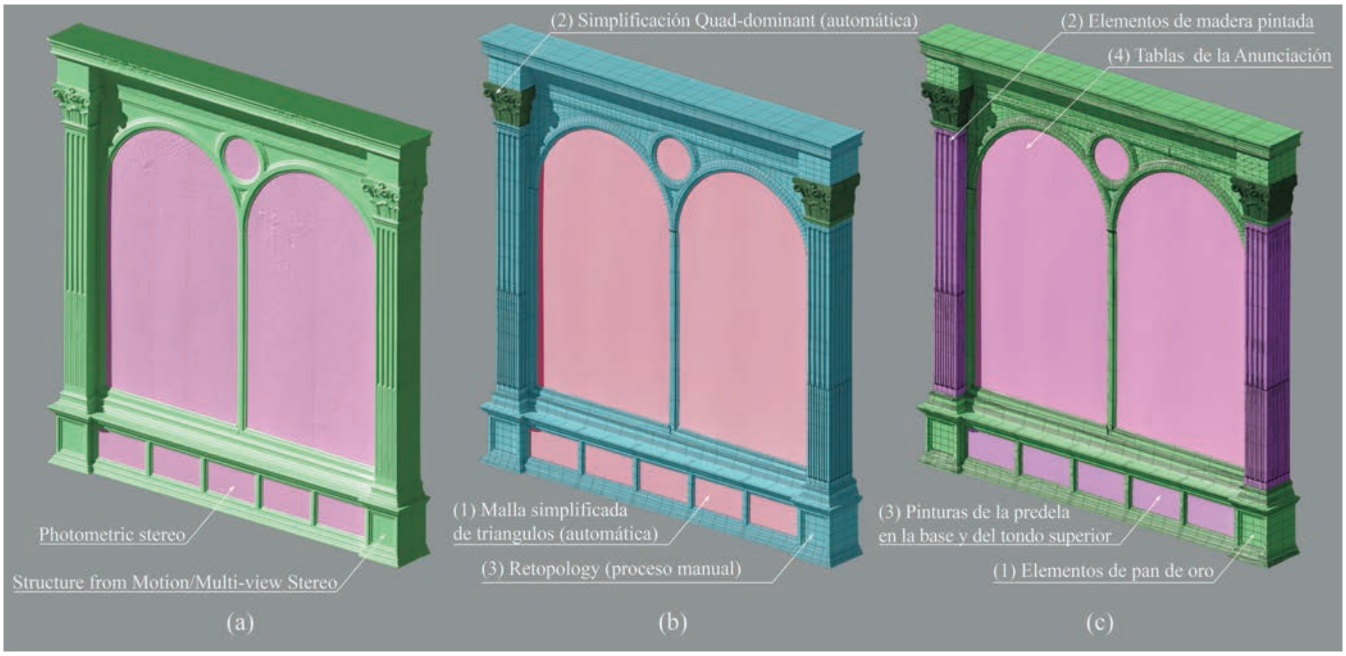

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the forthcoming divine motherhood to the Virgin, is a complex set of Marian symbolisms, depicted with saturated and engaging colors such as the red of the angelic dress or the lapis lazuli blue of the mantle of the Virgin. However, it is the magnificent gold leaf decoration, dedicated to the details of the garments and the halos of the figures, that catalyzes the attention of the observer, projected into a story where light, as well as the resulting color, becomes the protagonist. The system developed to digitally visualize Angelico's masterpiece, called *AnnunciatiOnApp*, pays specific attention to the definition of its 3D model, the visualization of complex materials such as the gold leaf that characterizes it and the removal of shadows due to the lighting conditions of acquisition (Fig. 1).

tométrica (*photometric stereo*) (WOODHAM, 1980), capaz de proporcionar con precisión la mesoestructura de la obra de arte (es decir, toda la serie de pequeñas protuberancias y variaciones que caracterizan la superficie de la pintura y que se califican con espesores que oscilan entre 20 mm y 2-3 mm) y las restantes propiedades ópticas de la superficie.

AnnunciatiOnApp integra las tres técnicas para explotar sus ventajas y eliminar sus defectos con el objetivo de proporcionar la forma, el color y las propiedades reflectantes de la superficie.

La digitalización del marco del cuadro, así como la del entorno general en el que se inserta la obra –imprescindible para llevar a cabo la eliminación de sombras de las imágenes adquiridas–, se realizó mediante un levantamiento fotogramétrico (Fig. 2) apoyado por un escaneado láser para escalar y verticalizar el modelo **8**.

Mientras que la superficie del tablero de madera del cuadro no recibió tratamiento posterior para mantener la resolución de requerida de 20 mm, el modelo del marco se sometió a un doble tratamiento (Fig. 3):

- *Remeshing* global de tipo *quad-dominant* (malla de polígonos con predominio de cuadrángulos) (JAKOB et al., 2015; APOLLONIO et al., 2021a);
- Retopología de los elementos arquitectónicos regulares del marco realizable mediante sencillas operaciones de extrusión y "puente" (CIPRIANI y FANTINI, 2015).

El modelo así generado se dividió en cuatro mallas diferentes optimizadas para una visualización eficaz en *Real-Time Rendering* (RTR):

- Elementos de pan de oro (entablamento, capiteles, pedestal, marcos moldeados de la predela y pintura).
- Elementos de madera pintada (pilares acanalados de la cornisa).
- Paneles de la *Annunciazione*.
- Pequeñas pinturas de la predela en la base y redondel en la parte superior.

Cada malla corresponde a una parametrización específica destinada a reconocer las partes individuales o los elementos constructivos del modelo optimizado para facilitar el control en la fase de "recuperación" de las sombras pronunciadas presentes en la textura, y a un sombreado específico destinado a reproducir en la fase de renderizado el comportamiento del material que representa a la luz: dieléctrico (pintado, elementos pintados) o conductor (pan de oro, elementos con marco de oro).

Para eliminar y suavizar las sombras en las texturas de estas mallas, se ha desarrollado un método basado en un flujo de trabajo que puede resumirse como sigue:

1. Reconstrucción tridimensional simplificada de la escena;

2. Reconstrucción digital del sistema de iluminación artificial que afecta a la obra y su importación al modelo tridimensional de la escena. En concreto, la posición y orientación de los tres grupos de focos que iluminan la obra se obtuvo a partir del levantamiento fotogramétrico realizado en la sala, mientras que el sólido fotométrico se obtuvo a partir de la documentación facilitada por el fabricante (Fig. 4);

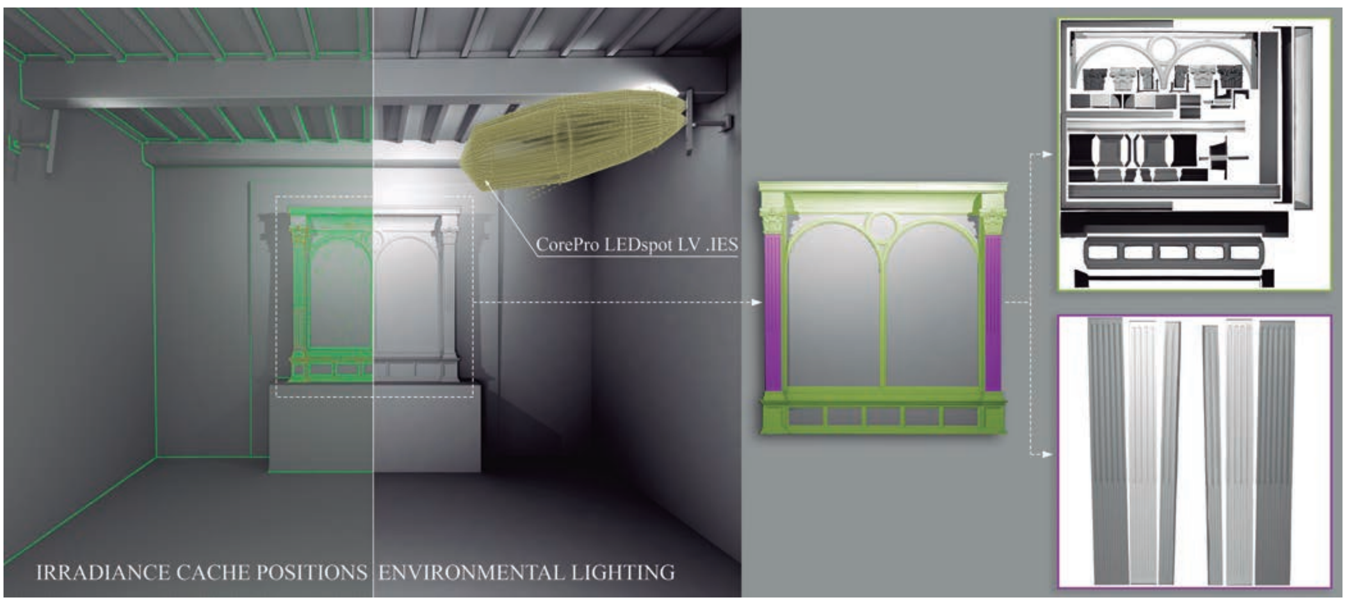
2. Posiciones de cámara para el levantamiento fotogramétrico: (a) posiciones con eje óptico ortogonal al cuadro; (b) posiciones con eje oblicuo para el marco superior y la predela; (c) pilares; (d) capiteles
3. (a) técnicas diversificadas para la adquisición fotogramétrica; (b) procedimientos de modelado para la optimización de modelos 3D; (c) segmentación del modelo 3D en función del comportamiento óptico a reproducir en RTR
4. Reproducción de la escena y del relativo set de iluminación con el objetivo de guardar la información de iluminación en texturas especiales en formato OpenEXR

2. The network of photogrammetric shots: (a) set with optical axis orthogonal to the painting; (b) oblique shots for upper frame and predella; (c) Pillars; (d) Capitals
3. (a) Diversified techniques for the photogrammetric acquisition. (b) Modeling procedures for the 3D model optimization. (c) Model segmentation based on the optical behaviors to be reproduced in RTR
4. Reproduction of the scene and the relative lighting set with the aim of saving the lighting information in special textures, stored in OpenEXR format

Construction of the three-dimensional digital model of the painting and the exhibition environment

The acquisition and construction of the 3D model of the *Annunciation* was carried out using photographic techniques only and it was generated with the integration of the two most common solutions used to digitize the paintings **7**:

- Gigapixel imaging, which is accurate in image resolution but limited to simple apparent color reproduction, and without any ability to show the three-dimensionality of the painting and its reflectance properties



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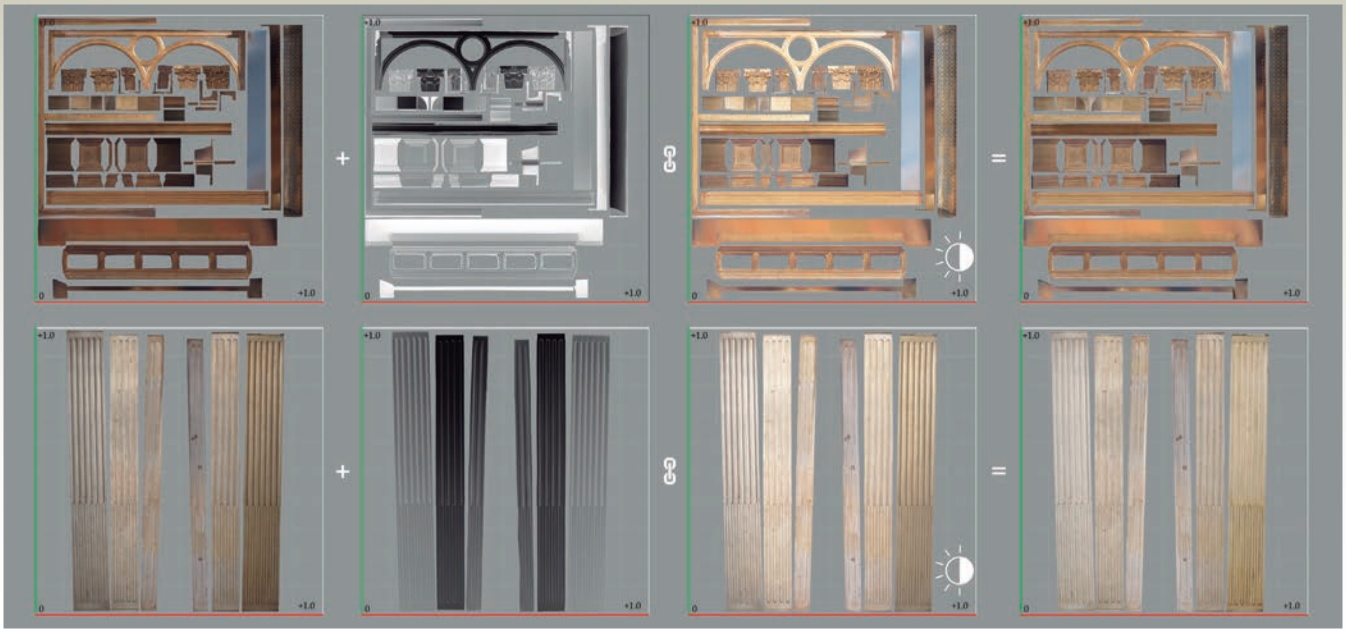

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(CABEZOS-BERNAL, RODRIGUEZ-NAVARRO and GIL-PIQUERAS, 2021);

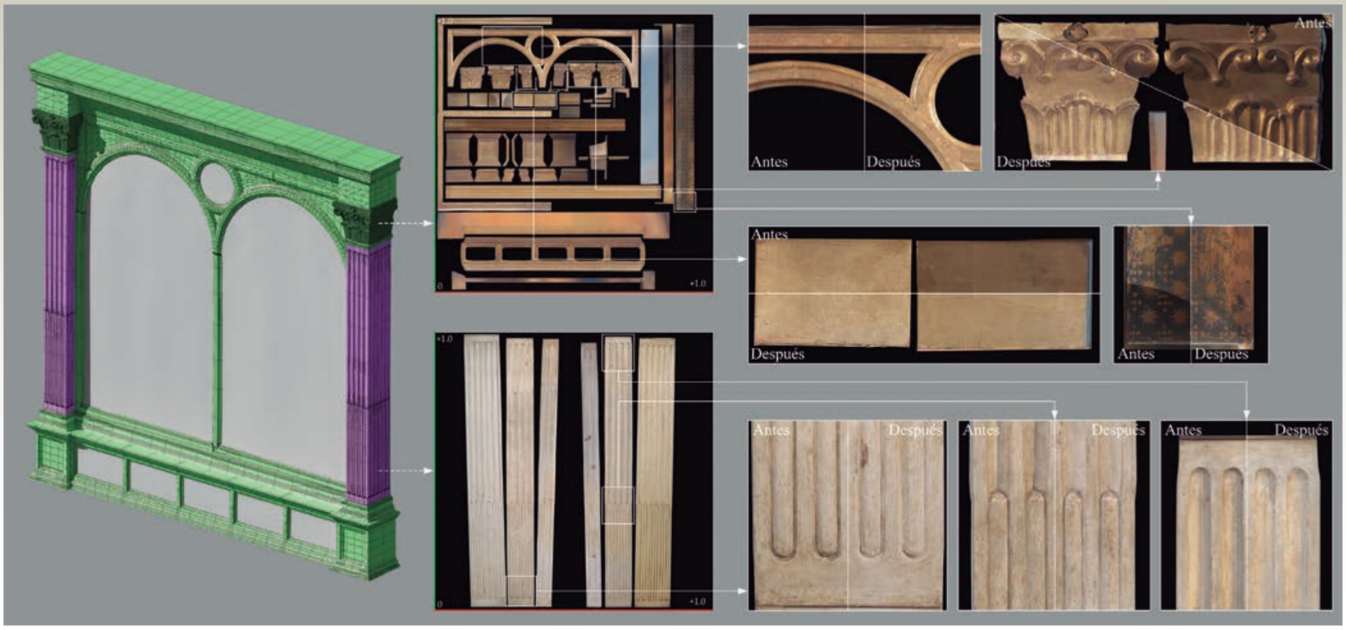
- 3D modeling based on automatic photogrammetry, accurate in metric reproduction and 3D characteristics, but generally not in chromatic replication and, in any case, unable to reproduce most of the reflectance properties (REMONDINO et al., 2011).

A third technology has been added to them, the photometric stereo technique (WOODHAM, 1980), capable of accurately restoring the mesostructure of the work of art (i.e., all that series of small bumps and variations that characterize the surface of the painting and which are characterized by thicknesses that vary between 20 µm and 2-3 mm.) and the remaining optical properties of the surface. *AnnunciatiOnApp* integrates these three techniques to exploit their advantages and eliminate their deficiencies, with the aim of restoring the shape, color, and reflectance properties of the surface. The digitization of the painting frame, as well as that of the general environment in which the work is placed - essential for removing the shadows from the acquired imagery - was performed through a photogrammetric survey (Fig. 2) supported by laser scanning to scale and verticalize the model **8**.
While the wooden panel surface of the painting did not receive post-processing to maintain the design resolution in 20 µm, the frame model was subjected to a double treatment (Fig. 3):

- Overall quad-dominant remeshing (JAKOB et al., 2015; APOLLONIO et al., 2021a);

3. Ejecución de un número de “baking” de iluminación (directa y indirecta) igual al número de mallas que componen la obra **9**;

4. Filtrado de las texturas de color aparente obtenidas de la fotogrametría con el “baking” de la iluminación mediante una serie de pasos semiautomatizados. La imagen de partida es la imagen de color aparente obtenida por reproyección de los fotogramas sobre el modelo optimizado y “fusionado” en el sistema de referencia (*u,v*) (Figs. 5 y 6), partiendo de imágenes sometidas a recuperación radiométrica mediante la explotación de la solución de corrección de color basada en objetivos y totalmente automatizada desarrollada por nuestro grupo de trabajo denominada SHAFT (SAT & HUE *Adaptive Fine Tuning*) (GAIANI y BALLABENI, 2018). Esta imagen presenta zonas subexpuestas y zonas con sombras nítidas evidentes que se eliminan automáticamente mediante el mapa de bits que captura la solución de iluminación directa y indirecta de la escena. Esta imagen se obtiene mediante una solución “render-to-texture” y se guarda en formato OpenEXR (KAINZ, BOGART y HESS, 2004) a 16 bits por canal, es decir, en formato HDR (*High Dynamic Range*) (REINHARD et al., 2005), para preservar todas las variaciones de intensidad luminosa con la máxima densidad de información permitida. La imagen HDR, antes de utilizarse para filtrar la textura de color, se somete a un estiramiento del histograma para mejorar su contraste (PRATT, 2007). El estiramiento del histograma se define fijando dos zonas de muestra: la primera representa el estado de iluminación de las zonas que reciben luz directa, la segunda las zonas de sombra, que están más ocluidas a la radiación luminosa y para las que es imposible utilizar un blanco cromático para anidar en zonas tan pequeñas. Estas zonas de muestra sirven de entrada para los valores tonales correspondientes a las sombras más intensas y a las zonas correctamente expuestas, estas últimas no se modifican. El último paso relativo al mapa de luminosidad es su compresión a 8 bits mediante técnicas de mapeo tonal; en particular, se utilizó la solución de Reinhard y Devlin, que al ajustar las altas luces extremas de la gama tonal genera un impacto mínimo en las sombras extremas (REINHARD y DEVLIN, 2005);



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5. Secuencia de pasos para la eliminación de sombras y claroscuros de texturas obtenidas por fotogrametría
6. La partición semántica del marco y las texturas de color relacionadas corregidas mediante el proceso descrito

5. Shadows and chiaroscuro phenomena removal steps from the textures produced by photogrammetric techniques
6. The semantic partitioning of the frame and the related color textures corrected by the described process

5. Por último, la imagen que representa el mapa de luminosidad se ajusta como nivel de transparencia a la imagen que representa la textura de color.

La reproducción del oro en el modelo 3D de la *Anunciación*

El renderizado realista basado en principios físicos para la descripción matemática del comportamiento de los materiales es una característica cada vez más común del software de visualización 3D en tiempo real (AKENINE-MÖLLER, HAINES y HOFFMAN, 2018), incluidos los últimos motores RTR destinados a juegos fotorrealistas (EBERLY, 2015; SALAMA y EL-SAYED, 2018; ZARRAD, 2018), como el disponible en Unity3D y denominado *High Definition Rendering Pipeline* (HDRP), que hemos utilizado.

Para simular cómo la luz, el cuadro y el punto de vista de un observador pueden interactuar entre sí, el comportamiento de la superficie del cuadro y de los marcos se modelizó no sólo a macroescala (la geometría general), sino también a mesoescala (es decir, la escala de la topografía), y a microescala (es decir, a 5-10 mm, la escala a la que la luz interactúa con las superficies que caracterizan las propiedades ópticas de los materiales) (ANDERSON, 2011).

En particular, para esta última, se partió de la hipótesis de que la superficie pictórica nunca es perfectamente plana, sino que puede asimilarse en microfacetas (TORRANCE y SPARROW, 1967). Por consiguiente, la modelización de los materiales de la *Annunciazione* se basó en la descripción del efecto de la dispersión de la luz, expresado por la función de distribución bidireccional de la dispersión (*Bidirectional Scattering Distribution Function* - BSDF), una magnitud que expresa el comportamiento

- Retopology of the regular architectural elements of the frame which can be obtained through simple operations of extrusion and connection via bridge (CIPRIANI and FANTINI, 2015).

The model, generated this way, was divided into four different optimized meshes to have an efficient display in Real-Time Rendering (RTR):

- Gold coated elements (trabeation, capitals, pedestal, molded frames of the predellas and of the picture);
- Elements in painted wood (coated pillars of the frame);
- Panels of the *Annunciation*;
- Small paintings in the predella at the base and in the roundel at the top.

Each mesh corresponds to a specific parameterization aimed at recognizing the individual parts or construction elements of the optimized model. This allows:

- Ease control in the recovery phase from the sharp shadows in the texture;
- To have a specific shader for each material to reproduce accurately its behavior at rendering runtime: dielectric (painting, painted elements) or conductor (gold leaf, gilded elements of the frame).

Based on the following workflow, a method for removing and attenuating shadows on textures has been developed:

1. Simplified three-dimensional reconstruction of the scene;
2. Digital reconstruction of the artificial lighting system that affects the work and

its import into the 3D model of the scene. Specifically, the position and orientation of the three groups of spotlights that illuminate the painting was inferred by the photogrammetric survey performed on the room, while the photometric solid was obtained from the documentation provided by the manufacturer (Fig. 4);

3. Creation of as many lighting *bakings* (direct and indirect) as there are meshes that make up the work **9**;

4. Filtering of the apparent color textures obtained from photogrammetry with lighting baking through a series of semi-automated steps. The starting image is the apparent color obtained by reprojection of the frames on the optimized model and 'merged' in the (*u,v*) reference system (Figs. 5 and 6), starting from images subject to radiometric recovery by exploiting the fully automated solution of target-based color correction developed by our working group and called SHAFT (SAT & HUE Adaptive Fine Tuning) (GAIANI and BALLABENI, 2018) This image has underexposed areas and areas with obvious sharp shadows that are automatically removed through the bitmap that incorporates

de los materiales cuando la luz se refleja o se transmite a través de ellos (WALTER et al., 2007).

Para evitar las complejidades matemáticas y las dificultades de parametrización de materiales que se obtienen mediante procesos artesanales sin control y no mediante técnicas industriales normalizadas, se ha recurrido a la formalización simplificada que proporciona *Disney Physically-Based Shading*, que da prioridad a la exactitud de la reproducción frente a la fidelidad analítica del modelo físico y permite una evaluación empírica de los fenómenos que caracterizan ópticamente los materiales (BURLEY, 2012, 2015).

Este formalismo, realizado mediante la aplicación de un sombreado (*shader*), ya ha demostrado su versatilidad y precisión perceptiva en el caso de la reproducción de dibujos y manuscritos antiguos (APOLLONIO et al., 2021b). En la realización del modelo de la *Annunciazione*, el sombreado se perfeccionó y modificó para representar plenamente tanto el temple cubierto de barniz transparente como las partes del cuadro realizadas en pan de oro.

En el caso concreto del oro del cuadro, el *shader* se obtuvo mediante dos operaciones:

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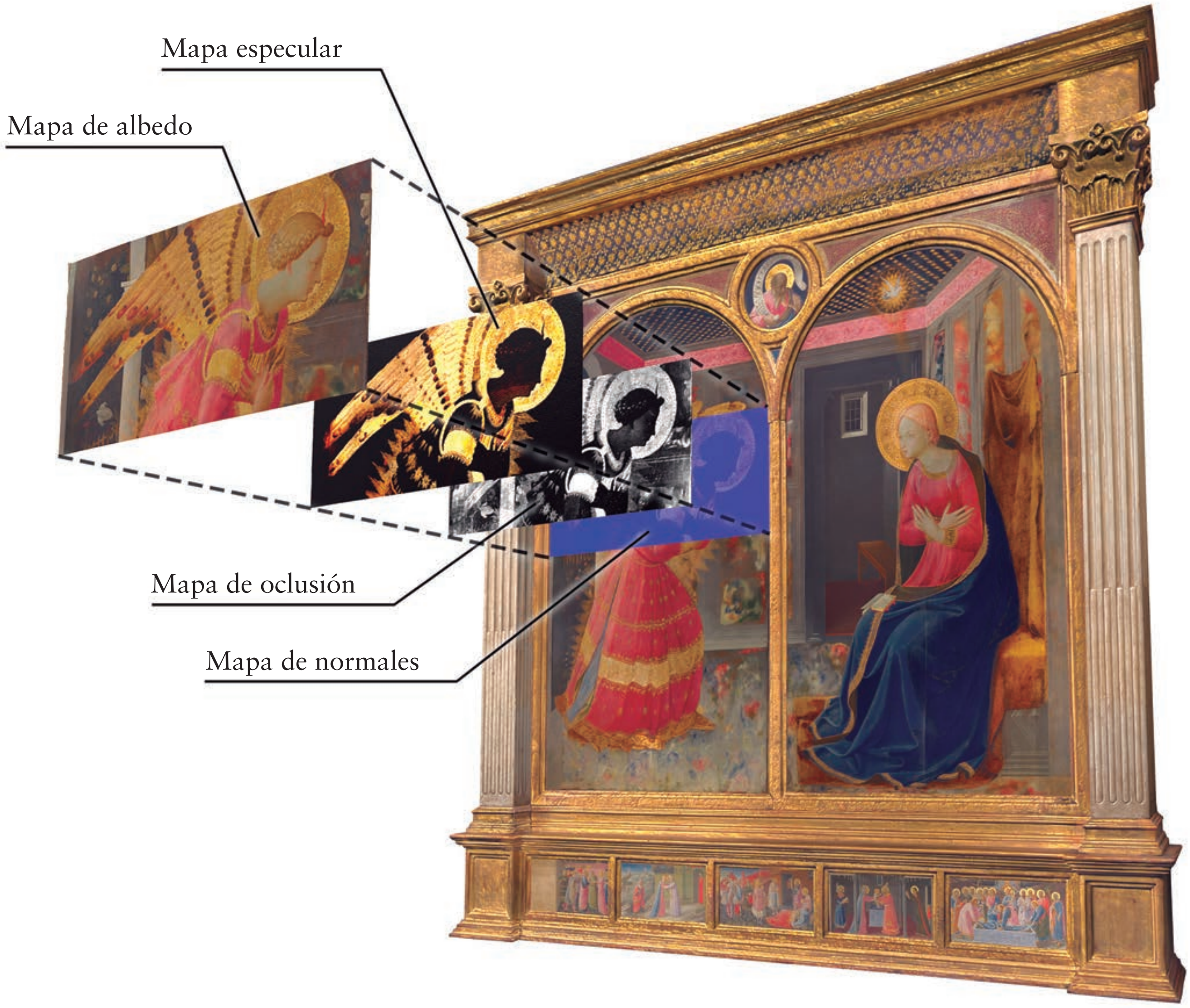
7. Un ejemplo de percepción de las propiedades ópticas del material del pan de oro, tal como se replica en el modelo tridimensional de la *Anunciación*: a medida que varía el ángulo de incidencia de la fuente de luz, el material refleja la energía de forma conservadora, de manera similar al comportamiento de la verdadera decoración

8. La composición de los diferentes mapas de albedo, reflexión especular, normal y emisividad de los materiales en la estructura del *shader* desarrollado en Unity3D, tal como lo produce la solución dedicada *nLights*

7. An example of perception of the optical properties of the gold leaf material, as replicated in the three-dimensional model of the Annunciation: as the incidence angle of the light source varies, the material reflects the energy conservatively, similarly to the behavior of the real decoration

8. The composition of the different albedo, specular reflection, normal and emissivity maps of the materials in the shader structure developed in Unity3D, as produced by our dedicated nLights solution



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- Se incluyó en el código un componente capaz de replicar la reflectividad especular. En particular, para reproducir el pan de oro, partiendo de las consideraciones de ARTEAGA et al. (2022) se investigaron en la literatura los parámetros útiles para describir su comportamiento, como su índice de refracción (igual al valor normalizado 0,470 **10**) (Fig. 7);
- Al adquirir la pintura, se evaluó el comportamiento de la reflexión especular del material muestreándolo a 45° y 20° con respecto al plano de la pintura, con el fin de evaluar con mayor precisión las normales de la superficie y especialmente el ángulo crítico de reflexión para materiales brillantes como el oro, en comparación con la solución tradicional de cuatro luces (COX y BERNS, 2015). Operativamente, el software estéreo fotométrico que desarrollamos a partir del *toolbox* para PSBox de Matlab (XIONG, 2023), reconstruye una serie de mapas de bits llamados por el *shader* en tiempo de ejecución por píxel, a partir de las tomas de adquisición de albedo, reflexión especular, normales y de oclusión de los diferentes materiales (Fig. 8).

Conclusión

La pintura italiana de principios del siglo XV seguía utilizando ampliamente temas prerrenacentistas como la acentuación de luces y som-

the direct and indirect lighting solution present in the scene. This image is obtained through a 'render-to-texture' solution and is saved in OpenEXR format (KAINZ, BOGART and HESS, 2004) at 16 bits per channel, i.e., in HDR (High Dynamic Range) format (REINHARD et al., 2005), to preserve all the variations in light intensity with the maximum permissible information density. The HDR image, before being used to filter the color texture, is subjected to a histogram editing, to improve the contrast (PRATT, 2007). This histogram stretching is defined by fixing two sample areas: the first representative of the lighting condition of the areas receiving direct light, the second of the shaded areas, more occluded to light radiation and for which it is impossible to use a chromatic target to be nested in such small areas. These sample areas serve as input of the tonal values corresponding to the most intense shadows and of the correctly exposed areas, the latter to be left unchanged. The last step concerning

9. Diferentes condiciones de iluminación obtenidas mediante imágenes HDR del entorno. El modelo y las texturas son flexibles y no se ven afectados por condiciones de levantamiento específicas

9. Different lighting conditions obtained by HDR imaging of the environment. The model and textures appear flexible and not affected by the specific environmental conditions

the luminosity map is its compression to 8 bits using tone mapping techniques. The solution of Reinhard and Devlin was used which by regulating the extreme lights of the tonal range generates a minimum impact on the extreme shadows (REINHARD and DEVLIN, 2005);

5. Finally, the image representing the luminosity map is set as transparency level to the image representing the color texture.

The gold reproduction in the 3D model of the *Annunciation*

The realistic rendering based on physical principles for the mathematical description of the behavior of materials is an increasingly widespread feature of real-time 3D visualization software (AKENINE-MÖLLER, HAINES and HOFFMAN, 2018), including the most recent RTR engines meant for photorealistic gaming (EBERLY, 2015; SALAMA and ELSAYED, 2018; ZARRAD, 2018), such as the one available in Unity3D and called High-Definition Rendering Pipeline (HDRP), which we used.

To simulate how light, the painting, and an observer's point of view can interact with each other, the behaviors between the surface of the painting and the frames have been modeled not only at the macroscale (the general geometry), but also at the mesoscale (i.e. say at the scale of topography), and at the microscale (i.e. at 5-10 μm, the scale where light interacts with surfaces characterizing the optical properties of materials) (ANDERSON, 2011).

For the latter we started from the assumption that the pictorial surface is never perfectly flat, but that it can be assimilated to micro-facets (TORRANCE and SPARROW, 1967). For this reason, the materials modeling of the Annunciation was based on the description of the effect of light dispersion, expressed by the Bidirectional Scattering Distribution Function (BSDF), a quantity that expresses the behavior of materials when light is reflected or transmitted through them (WALTER et al., 2007).

To avoid mathematical complexities and difficulties in finding parameters for materials that are obtained from artisanal processes, without control and from not standardized industrial techniques, the

(a) (b) (c)

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bras mediante el enriquecimiento del cuadro con técnicas basadas en el pan de oro. Al mezclar estas técnicas con los nuevos desarrollos de la pintura renacentista, dados esencialmente por la representación en perspectiva de cuadro vertical, Fra Angelico fue sin duda un maestro, y ciertamente sus *Anunciaciones*, como la de San Giovanni Valdarno, representan los mejores ejemplos.

La reproducción digital de las particularidades de este estilo de pintura, reproduciendo correctamente todas sus propiedades ópticas, es todavía hoy un problema sin solución.

En esta contribución se presentan las características de un método aplicado para replicar visualmente las propiedades ópticas de un material complejo como el pan de oro, con el fin de representar lo más fielmente posible la luz reflejada y eliminar las sombras propias y arrojadas guardadas en las texturas en el momento de la toma fotográfica.

Frente a los criterios tradicionales de documentación fotográfica, en los que la bidimensionalidad de los objetos representados constituye ya una limitación en el conocimiento de la obra de arte, se ha demostrado cómo un modelo tridimensional, producido para ser visualizado interactivamente, es portador de una información más completa sobre todo cuando es capaz de replicar el comportamiento a la luz del original. Cuando la verosimilitud perceptiva del modelo es adecuada para describir con detalle una pintura articulada, como en el caso de la *Annunciazione* de Fra Angelico, puede revelar nuevos aspectos útiles tanto para comprender cómo se produjo la obra como para preservarla en el tiempo (Fig. 9). ■

Notas

1 / Una documentación fiable también ofrece una base precisa para estudios de carácter proporcional (GARCÍA-CÓRDOBA et al, 2022).
2 / Utilizando técnicas como las descritas en BARNES et al. (2011). Sobre el flujo óptico basado en aprendizaje profundo y el PatchMatch guiado con autocurado ver ZHENG et al. (2022) y ZHANG et al. (2022). Dichos algoritmos se implementan hoy en día en Adobe Photoshop como Adobe Content-Aware Fill, que son adecuados para situaciones de fuerte contraste (sombras nitidas) pero no apropiados para corregir fenómenos de claroscuro, además de ser una solución no aplicable a vastos conjuntos de fotos como en el presente caso.
3 / Véase una reseña completa en FINLAYSON et al. (2006). Además, el mas reciente MURALI, GOVINDAN y KALADY (2021).
4 / Sobre las distintas formas de parametrización de los modelos poligonales see HORMANN, KONRAD y SHEFFER (2008).
5 / La exposición, comisariada por Michela Martini, Daniela Parenti, Carl Brandon Strehlke y Valentina Zucchi, estuvo abierta del 17 de septiembre de 2022 al 15 de enero de 2023.
6 / Sobre la Anunciación véase MARTINI, PESCI y SACCHETTI (2019); MARTINI y BONI (2022); GONZÁLEZ MOZO (2019); STREHLKE (2022) y STREHLKE (2019).
7 / Las imágenes adquiridas se sometieron a un procedimiento de corrección del color mediante el software SHAFT, que utiliza un flujo de trabajo de varias etapas, entre ellas, una está dedicada al balance de blancos (GAIANI y BALLABENI, 2018). En la adquisición de San Giovanni Valdarno, la temperatura de color de las lámparas Relio2 se evaluó en torno a 4047°K, debido a las especificaciones técnicas certificadas por el fabricante, que realizó pruebas de laboratorio con un espectrofotómetro puesto a disposición de los usuarios (Relio2 Light Quality Reports v1.00). [Online]. Available: https://www.relio.it/user/themes/relio2/docs/Relio%C2%B2%20-%20Light%20Quality%20Report.pdf). [Accessed: 18-mayo-2023]. También se utilizó un filtro polarizador para atenuar los fenómenos de reflexión especular intensa.
8 / Se utilizó un escáner láser Faro Focus 3D X 130, de 2 mm de resolución a 10 m, con una incertidumbre de medición de 0,15 mm.
9 / Este proceso de baking es de tipo “anidado”, ya que escribe la solución de iluminación del modelo de alto detalle en el espacio de parámetros (u,v) del modelo simplificado.
10 / Conservation and Art Materials Encyclopedia Online (CAMEO).

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simplified formalization provided by Disney Physically Based Shading was used, which favors accuracy of reproduction over to the analytical fidelity of the physical model and which allows an empirical evaluation of the phenomena that optically characterize the materials (BURLEY, 2012, 2015).
This formalism, achieved through the implementation of a shader, already demonstrated its versatility and perceptual accuracy in the case of the replication of ancient drawings and manuscripts (APOLLONIO et al., 2021b). In the creation of the Annunciation model, the shader was further refined and modified to fully represent both the tempera covered with transparent varnish and the portions of the painting made in gold leaf.
In the specific case of the gold leaf used in the painting, the shader was generated through two operations:

- a component capable of replicating specular reflectivity has been included in the code. To reproduce the gold leaf, starting from the considerations of ARTEAGA et al. (2022), the parameters useful for describing its behavior have been researched in the literature, such as its index of refraction (equal to the normalized value 0.470 **10**) (Fig. 7);
- during the acquisition of the painting, the behavior of the material to specular reflection was evaluated, sampling it at 45° and 20° with respect to the painting plane to evaluate the surface normals more accurately and, above all, the critical angle of reflection for shiny materials like gold, compared to the traditional four-light solution (COX and BERNS, 2015). From an operational point of view, our stereo photometric software developed starting from the PSBox toolbox for Matlab (XIONG, 2023), reconstructs per-pixel a series of bitmaps recalled by the shader in the runtime phase, starting from the albedo, specular reflection, normal and occlusion acquisition shots of the different materials (Fig. 8).

Conclusions

Italian painting of the early fifteenth century still makes extensive use of themes from the era prior to the Renaissance, such as the

accentuation of light and shadow through the enrichment of the painting using techniques based on gold leaf. In mixing these techniques with the new approaches, typical of Renaissance painting, given essentially by the perspective representation of a flat picture, Fra Angelico was certainly a master and surely his Annunciations, including that of San Giovanni Valdarno, are the best examples.
The digital reproduction of the characters of this painting style, correctly reproducing all its optical properties, is still an unsolved problem today.
In this contribution, the characteristics of a method applied to visually replicate the optical properties of a complex material such as gold leaf were presented to replicate the reflected light as faithfully as possible, and to eliminate the own and cast shadows in the images upon acquisition.
Compared to the traditional criteria of photographic documentation, in which the two-dimensionality of the objects represented already constitutes a limit in the knowledge of the work of art, it has been shown how a three-dimensional model, produced to be displayed interactively, is the bearer of more complete information, especially when it is able to replicate the light behaviors of the original. When the perceptive likelihood of the model is adequate in describing in detail an articulated painting, as in the case of the Annunciation by Fra Angelico, it can reveal new aspects, useful both for understanding how the work was produced and how it is possible to preserve it over time (Fig. 9) . ■

Notes

1 / Reliable documentation also provides an accurate basis for proportional and design analysis (GARCÍA-CÓRDOBA et al, 2022).
2 / Using techniques such as those described in BARNES et al. (2011). On deep learning-based optical flow and guided PatchMatch with self-healing see ZHENG et al. (2022) and ZHANG et al. (2022). Such algorithms are implemented today in Adobe Photoshop as Adobe Content-Aware Fill, which are suitable for situations of strong contrast (sharp shadows) but not suitable for correcting chiaroscuro phenomena, besides being a solution not applicable to vast sets of photos as in the present case.
3 / See FINLAYSON et al. (2006) for a full review. In addition, the more recent MURALI, GOVINDAN and KALADY (2021).
4 / On the various forms of parameterization of polygonal models see HORMANN, KONRAD y SHEFFER (2008).
5 / The exhibition, curated by Michela Martini, Daniela Parenti, Carl Brandon Strehlke and Valentina Zucchi, was open from September 17, 2022, to January 15, 2023.

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6 / On the Annunciation see MARTINI, PESCI y SACCHETTI (2019); MARTINI y BONI (2022); GONZÁLEZ MOZO (2019); STREHLKE (2022).
7 / The acquired images underwent a color correction procedure using the custom-developed SHAFT software, which uses a multistage procedure including a specific step dedicated to white balance (GAIANI and BALLABENI, 2018). In the San Giovanni Valdarno surveying, the color temperature of Relio[2] lamps was evaluated approximately equal to 4047°K, due to the technical specifications certified by the manufacturer, who performed laboratory tests with a spectrophotometer made available to users (Relio[2] Light Quality Reports v1.00). [Online]. Available: https://www.relio.it/user/themes/relio2/docs/Relio%C2%B2%20-%20Light%20Quality%20Report.pdf). [Accessed: 18-may-2023]. A polarizing filter was also used to attenuate intense specular reflection phenomena.
8 / A Faro Focus 3D X 130 laser scanner was used, 2 mm resolution at 10 m, with a measurement uncertainty of 0.15 mm.
9 / This baking process is of the "nested" type, since it records the illumination solution of the highly detailed model into the parameter space (*u, v*) of the simplified model.
10 / Conservation and Art Materials Encyclopedia Online (CAMEO).

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