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Digital Reintegration of Distributed Mural Paintings at Different Architectural Phases: the Case of *St. Quirze de Pedret*

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Abstract

Sant Quirze de Pedret is a Romanesque church located in Cercs (Catalonia, Spain) at the foothills of the Pyrenees. Its walls harbored one of the most important examples of mural paintings in Catalan Romanesque Art. However, in two different campaigns (in 1921 and 1937) the paintings were removed using the strappo technique and transferred to museums for safekeeping. This detachment protected the paintings from being sold in the art market, but at the price of breaking the integrity of the monument. Nowadays, the paintings are exhibited in the Museu Nacional d'Art de Catalunya - MNAC (Barcelona, Catalonia) and the Museu Diocesà i Comarcal de Solsona - MDCS (Solsona, Catalonia). Some fragments of the paintings are still on the walls of the church. In this work, we present the methodology to digitally reconstruct the church building at its different phases and group the dispersed paintings in a single virtual church, commissioned by the MDCS. We have combined 3D reconstruction (LIDAR and photogrammetric using portable artificial illumination) and modeling techniques (including texture transfer between different shapes) to recover the integrity of the monument in a single 3D virtual model. Furthermore, we have reconstructed the church building at different significant historical moments and placed actual paintings on its virtual walls, based on archaeological knowledge. This set of 3D models allows experts and visitors to better understand the monument as a whole, the relations between the different paintings, and its evolution over time.

CCS Concepts

• ***Applied computing*** → ***Fine arts;*** *Architecture (buildings);* • ***Computing methodologies*** → *Computer graphics;*

1. Introduction

The use of digital tools for the virtual reconstruction of Cultural Heritage undoubtedly facilitates an improvement in the perception and experience of the visitors. If we consider medieval monuments, preserved with profound transformations due to the alterations suffered over the centuries, and with the decorative elements relocated in different museums, the possibilities for visitors to understand them without digital tools are very narrow. The case we present in this paper is the digital reconstruction of the small church of Sant Quirze de Pedret (Cercs, Catalonia), which contains mural paintings that are among the finest examples of European Romanesque painting [CG14, Cay22]. From an earlier 9^{th} century building with a nave and an apse, a new church was built in the 10th century with a nave and two aisles with a wooden roof and three vaulted apses. This church was first decorated at the beginning of the 11^{th} century with mural paintings [Man12], which remained under a new and rich decoration layer executed at the beginning of the 12^{th} century. In the 13th century, the church was deeply transformed by the substitution of part of the south aisle with a portico, the consequent transfer of the door to the central nave, and the construction of vaults that covered part of the paintings [LMCM95]. In June 1921, as part of the campaign to remove Pyrenean mural paintings carried out by the Barcelona Museums Board between 1919 and 1923, the paintings were removed from the side apses of Pedret, which were restored and exhibited in the Barcelona Museum (now the *Museu Nacional d'Art de Catalunya - MNAC*) from 1924 onwards. During the Spanish Civil War, in 1937, the paintings of the central apse were removed along with the pictorial fragments located underneath the Romanesque paintings and were taken first to Barcelona and later to the *Museu Diocesà i Comarcal de Solsona - MDCS* (Solsona, Catalonia). Figure 1 shows the current state of the church building of Pedret (left) and its paintings exhibited in MDCS (center) and MNAC (right). During the restoration of the church, new fragments of paintings were found and are preserved in situ.

The paintings were mounted in regular structures that imitate the original architecture: apses, arches, and walls (Figure 1). However, their differences from the original walls, combined with the manual assembling process, resulted in small, but relevant, deformations of the exhibited paintings. Moreover, the architectural context

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Figure 1: *Current situation of the interior of St. Quirze de Pedret (central nave and central and north apse, left) and the exhibition of its paintings in MDCS (central nave and apse, center) and MNAC (north and south apse, right). The fragmentation of the artworks in three different locations considerably complicates its understanding.*

recreated in the respective museums is insufficient to understand the ensemble, because some paintings are in Solsona and others in Barcelona, and both are separated from the original provenance. In addition, the iconographic cycles represented in Pedret are not the most common in Romanesque painting. Therefore, we have a cultural heritage sample presenting some challenges that, to the best of our knowledge, have been rarely handled as a whole. For the sake of better understanding and interpretation, the goal of this work was to *regroup* the paintings and show the existence of different paintings layers.

The 3D reconstruction consisted of the creation of five architectural models to understand the evolution of the church over the centuries in its different construction phases, including the current one. The diachronic perspective is, therefore, one of the important axes of the project. This has been possible thanks to the huge amount of knowledge accumulated about the different construction periods of the building through extensive archaeological research. The 10^{th} century building underwent two decorative phases: at the beginning of the 11^{th} century and at the beginning of the 12^{th} century. The preserved wall paintings, thus, correspond to two decorative periods, being the older ones covered by the Romanesque ones.

For all these reasons, Pedret is a good example of the complexity and the difficulties of understanding a medieval building, once decorated with mural paintings, to the eyes of heritage curators and the interested visitors. In fact, the reproductions and unfortunate recreations carried out in the last restoration campaign in the church, have contributed more to the confusion than to the understanding of the whole set. It should be noticed that the return of the wall paintings to the original building is not feasible for multiple reasons: the different current ownership of each set of frescoes, the high risk of damaging the paintings, and the practical impossibility of superimposing again the two painting layers at the central apse.

The project we present here is the first virtual reconstruction of the church in its different architectonic and decorative phases. It has been commissioned by the Museu Diocesà i Comarcal de Solsona on the occasion of the refurbishment of the museography of the room in which Pedret's paintings are exhibited, to be included in an audio-visual presentation (see Figure 15). Its purpose, therefore, is clearly aimed at improving visitors' understanding and appreciation of the heritage. But it will also help experts to study and analyze the relations between different parts of the paintings that are currently exhibited in fragments more than one hundred kilometers away. The project is the application of multidisciplinary research results: from archaeology (the various excavation campaigns of the building and its surroundings for its restoration) and history of art, to architectural modeling and computer graphics.

2. Previous work

2.1. Digital 4D reconstructions for Cultural Heritage

Thanks to the advances in laser scanning and photogrammetry technologies, the 3D digitization of Cultural Heritage has become a common practice [FK18, PMG*20] to preserve, study and disseminate it. The benefits of digital 3D reconstruction of artifacts, monuments, and sites have been largely studied for different aspects of Cultural Heritage [BFS00, LSFK18]. Previous works have already shown high quality in the acquisition of appereance and shape. However, they usually use natural lighting [HAD*09, Sal20] or static artificial illumination [GMaMC09, JFY*09]. These setups have issues reconstructing the appearance with consistent lighting through the scene in situations, such as our case, with paintings on irregular, curved surfaces.

Digital 4D modeling refers to the creation of time-varying 3D reconstructions of Cultural Heritage objects to capture its variation during different historical periods. Current 3D acquisition technologies can be employed to obtain a precise 3D model of an existing object, but they obviously cover its status at the time it is digitized. The reconstruction of previous phases of the object presents important challenges, such as the data collection and integration over heterogeneous unstructured resources. For example, Doulamis et al. [DDP*18] discuss the 4D reconstruction of the historic city of Calw in Germany from unstructured image content from the web. Guidi et al. [GMM18] discuss the reconstruction of monuments that have almost entirely disappeared. They present a diachronic reconstruction approach to show the Roman Circus of Milan in its current state (using 3D surveys) and its presumed past appearance (using diverse historical sources including ancient maps, drawings, archaeological reports, and old photographs).

The European project named "Cultural Heritage Through Time" aimed at fully integrating the fourth dimension into Cultural Heritage studies to envisage lost sites or visualize changes due to anthropogenic activities or intervention, pollution, wars, earthquakes, or other natural hazards [HKM*17].

2.2. Re-contextualization of artworks

During the 20th century, many artworks were detached from their original setting and sold/moved to various museums for their exhibition or preservation. In 1931, Lionello Venturi wrote about the large number of artworks from Italy (mostly paintings) that ended up in US museums [Ven31]. This fragmentation of the artworks keeps visitors from understanding them in their context. In the case of mural paintings, museums often exhibit the artworks in a setup that only provides a partial reconstruction of the original setting (e.g., just one room); conversely, the original monuments display either the bare walls with the remainings of the paintings (often small traces of the deepest layers), or recreations of the original artworks.

Digital heritage has shown to be a valuable tool to partially close the gap between fragmented artworks and their provenance, and a few papers address the problem of re-contextualization of artworks in their original settings, based on 3D reconstructions. Fachechi et al. [FGL*19] discuss the use of digital 3D models to virtually put together dispersed Cultural Heritage, putting it into its historic-artistic context so that the works of art can be "enjoyed as though they were still all together in the same place, in their original layout.". Fachechi et al. applied this approach to the medieval frescoes of the Monastery of S. Maria Inter Angelos (Italy), preserved in various museums, mainly in the US [FGL*19].

The reunification of mural paintings in a 3D digital model of its provenance building requires transferring the color from photographs onto the 3D model. For flat surfaces of the digital model (e.g., room walls), the problem is easy as it just involves parameterizing the surface and projecting the color from registered photos onto the associated texture [FGL*19]. The color transfer from curved surfaces (e.g., mural paintings on apses) is a more challenging task, especially when the shape of the two surfaces (the original one at the monument, and the reconstructed regular support at the museums) differ substantially. This is actually one of our major methodological differences compared to [FGL*19], which only dealt with paintings on planar surfaces. At Pedret, the central and lateral apses were decorated with paintings and, thus, we had to deal with the re-integration of paintings on curved surfaces (Section 8).

In the context of medieval mural paintings, one example of such reunification is Taüll 1123, a project that uses digital video mapping to virtually transfer the original paintings preserved in the MNAC into the church of Sant Climent de Taüll [MRGC14, Sen20, FF20]. Mural paintings are delicate artworks that are affected by multiple deterioration conditions [SMFPSu]: humidity, weathering, ambient conditions, structural problems of the building causing delamination, and anthropogenic interventions are some of the factors affecting mural paintings. Soto-Martin et al. [SMFPSu] describe the digital reconstruction of the St. Augustine Church in La Laguna (Tenerife, Spain), which is in a state of advanced deterioration. The authors used photogrammetry to reconstruct its architectural features and recovered its highly deteriorated mural paintings using a color-enhancing digital imaging tool. Virtual restoration of paintings, although not universally considered suitable for all types of monuments, can be applied to attempt to recover the original state of the painting [Lim17].

3. Goals of the project

The digital reconstruction of the Pedret church in the different significant periods from the 9th century to now, with its different decorative campaigns, pursues the following objectives.

First, we aim to improve the understanding of a spread medieval heritage. The digital reintegration of the paintings, without applying any reconstruction, makes it possible to recover the unity of a heritage which, as a result of the recovery and safeguarding processes in the 1920s and 1930s, is now in three different locations as described in the introduction.

Second, we wish to show the monument in its diachronic evolution, both in terms of architecture and paintings. The church of Sant Quirze de Pedret is the result of three major construction phases, in the 9th, 10th - with additions in the 11th century -, and 13th centuries. The 10th century building received its first decoration in the 11th century and the second campaign of paintings at the beginning of the 12th century. The addition of a vault in the central nave in the 13th century meant that a part of the paintings was covered.

Finally, we want the audience to understand the mural paintings in their context and enhance their value. The Pedret mural paintings are among the finest in European Romanesque painting. They contain a highly original program of images without parallel in Catalan Romanesque painting. The pictorial decoration did not cover the entire church, only the liturgical spaces to which the monks and clerics had access: the three apses, the respective front arches, and the first section of the central nave. By virtually reintegrating the paintings into the original spaces, it is possible to experience the authentic liturgical setting of the Romanesque period. Nowadays, the transformations of the building and the conservation of the paintings at different locations prevent us from fully appreciating this outstanding collection of Romanesque paintings, which was designed in a rich cultural and intellectual environment, and executed by an excellent painter.

To fulfill the previous objectives, in this project, we have employed the following methodology. First of all, we performed an acquisition campaign in the three locations. We captured the shape of the church building and the museum mockups using a 3D scanner and the appearance of the paintings thanks to a photographic campaign. After that, we generated 3D models of the church at important historical moments. This process was based on the 3D captured data modified taking into account the historical and archaeological documentation and discoveries obtained during its restoration. Then, we created a 3D reconstruction of the paintings using a photogrammetric process adapted to take into account the particularities of the data. Afterward, we generated, and applied, the textures on the 3D models to simulate the appearance of all the church building parts not covered by paintings. Finally, we transferred the 3D reconstructed paintings to their exact position on the textured walls of the 3D models. Thanks to this methodology, we have been able to generate realistic reconstructions of the church, at each of the historical moments, exhibiting the corresponding paintings of each moment that have been preserved up to now. The following sections describe in detail each of these methodology steps and show the obtained results.

4. Data collection

The first step of our project was to perform an acquisition campaign on the three locations. The goal was to capture the shape (geometry) and appearance (color) of the church building and its paintings.

We captured the surface through a 3D scanning process. We used a Leica RTC360 laser scanner (see Figure 2 left). This scanner is quite fast and accurate, with user-selectable resolution settings up to 3 mm @ 10 m. The scanner provides High Dynamic Range

Figure 2: *The acquisition of the data was a two-step process for the three locations: we captured the surface using a laser scanner (left) and the appearance of the paintings using a specific photographic setup (right).*

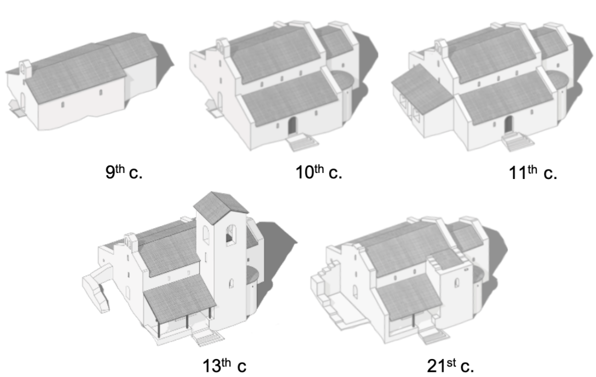

Figure 3: *Historical evolution of Sant Quirze de Pedret*

(HDR) 360 images by encompassing the information of multiple pictures with different exposures. The RTC360 also features automated, targetless, on-site registration.

In state-of-the-art laser scanners, the HDR images are used to colorize the point clouds. However, this technology has still some drawbacks. A first issue is that color information may exhibit color bleeding artifacts due to small misalignments between the panoramas and the point cloud, which is especially noticeable around surface edges. A second major issue is that color is not consistent across scans, since image enhancements (color balance, exposure correction) are applied per scan, which produces visual artifacts when combining multiple scans. Finally, although the resolution of HDR is very high, keeping a stable high sampling of the paintings implies performing a higher number of scans than those needed for the surface reconstruction, leading to a huge amount of redundant data. For these reasons, we also added as color source the pictures of a photographic campaign made by an expert photographer.

Digital representation of frescoes is a challenging task, especially when dealing with mural paintings in medieval churches. Besides the classic problems of accuracy in the digital representation of colors, these scenarios present their specific struggles. The accessibility to the different parts of the building, the different lighting conditions available throughout the spaces, and the conservation state of the paintings are some of the most common factors that make using a typical photogrammetric approach not feasible. In the photographic campaign (see Figure 2 right), the expert photographer used a Canon 6D Mark II DSLR camera. This camera has a high-quality full-frame sensor that allows us to maximize the sharpness and resolution of the images. He used several different lenses mounted on the camera, from wide angles to telephotos. This combination of lenses allowed him to keep, at the same time, stable the quality (i.e. high sharpness and low aberrations) of the acquisition and to overcome the limited accessibility of the different mural paintings. To handle the different lighting setups in the buildings, he used two Godox 600W flash units pointing at 45 degrees of the surface (one from left, one from above). This light schema gives consistency to the paintings emphasizing their texture at the same time. On the opposite side of the light source, he placed a white reflective panel to soften the shadows without losing surface details. During the capture, he kept a constant distance between the camera and the paintings. Moreover, he pointed at the paintings following an orthogonal direction to avoid distortions. He moved both flashes throughout the scene at each shoot to keep stable the amount of light that reached the visible surface. This way, he was able to enhance the texture and conservation state of the paintings consistently across the scene. Finally, he used an x-rite ColorChecker in every group of images taken with the same lighting and camera configuration. The use of a color checker is a standard calibration method to be able to reproduce colors with accuracy.

5. Generation of the architectural models

Five models of the church of Sant Quirze de Pedret were generated, corresponding to five moments of its historical evolution: 9th, 10th, 11th, 13th, and 21st centuries (Figure 3). Although the chronological order would suggest starting the process by modeling the church in its original state in the ninth century, the only verifiable geometric information is the one that emanates from the current state. Therefore the first step was to generate the 21st-century model from a point cloud survey. From archaeological studies and documentation of carried-out restorations, besides on-site observations itself, the invariants of the building were determined. That is, those characteristics that have survived unchanged from their origin to nowadays. Once these constants were identified, the work focused on recreating and completing the rest of the geometry of the church at each of the considered periods.

A 3D architectural model should include the specification of all the details of its geometric configuration. Unfortunately, the main source of archaeological studies does not go farther than the soil and subsoil levels. Consequently, apart from the conserved parts and the evidence brought by the work of archaeologists, the models we made unavoidably contain elements that are just hypothetical. They are insofar as they are not verifiable, but care has been taken to ensure that they are consistent with constructive logic and all available information. One of the main assets of 3D models is their ability to gather in a single and simultaneous view the available geometric information. This allows showing the relationship between the parts of the model, which, while not allowing an unequivocal answer to all the questions raised, it limits the range of possible solutions. On the other hand, the rigorous survey we made in Sant Quirze de Pedret allowed us to extract sections, elevations, and plans, at different heights, and to detect aspects of the geometry

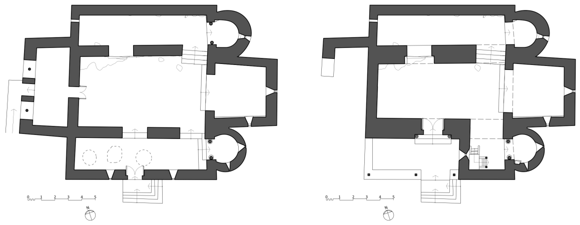

Figure 4: *Plans with the two aisles added in the 10^{th} c. (left) and the new configuration since the 13^{th} c. when the south aisle was removed (right).*

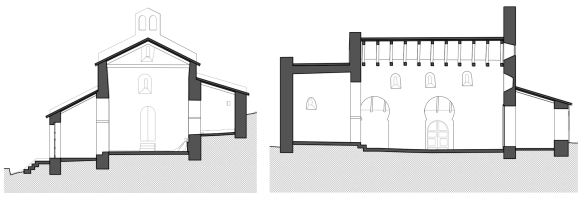

Figure 5: *Cross section looking to the west (left), where the different levels are appreciated, and longitudinal section (right) looking from north.*

of the building that are difficult to notice just by looking, and from which new hypotheses of the ancient buildings may be derived.

Contrary to what was assumed previously, the modeling process has shown that the outer surface of the 9th-century roof had to be continuous from the nave to the apse, despite the different interior roofing systems of each one. Likewise, also in the ninth century, the 3D model reveals a conflict in the resolution of the access considering the difference in height between the interior and exterior of the entrance.

There is also archaeological evidence that in the 10th century the church was enlarged with two aisles and had a new entrance at the south one (see Figure 4 left). The certainty that the access stairs to this south door are the ones that still exist nowadays shows that the floor of this aisle, disappeared since the 13th century (see Figure 4 right), must have been about 50 cm below that of the central nave and 60 cm bellow the floor of the south apse (see Figure 5 left). Steps were included to bridge the gap. Its specific layout is merely speculative, although it follows a certain architectural logic; but its existence, either with this or with an alternative layout, seems out of the question.

Studies indicate that, in the 11th century, a small building was erected attached to the western wall and its remains are still present. Everything seems to suggest that it was an aedicule to protect the door on this side, but little is known beyond the floor plan and part of its north wall. It is also unknown how the bell tower, built in the 13th century, was completed and how it was accessed. But the respective models cannot leave these questions unanswered. In the first case, given the vagueness of the subject and the doubts it raises, the interpretation given by the last restorers has been followed. In the case of the bell tower, inspiration has been sought from geographically close and contemporary models.

6. Reconstruction of the mural paintings

As we already have mentioned in Section 4, nowadays, scanning techniques are not still able to reproduce surface colors with quality and detail. Photographs, in contrast, are a simple way to achieve high-quality digital representations of the colors an object exhibits. However, images store color information in 2D. Although one can project 2D data onto a 3D model, this process is usually manual and turns complex when the number of images increases. Fortunately, photogrammetry can convert sets of images into 3D data automatically. First, it estimates camera poses for each image using a Structure from Motion algorithm (e.g. [SF16]). Then, it generates a 3D model combining estimated depth information for each camera (e.g. [FG11]). Finally, it builds a texture for the model combining the original photographs thanks to a texture blending technique (e.g. [WMG14]).

Using photogrammetry may seem a straightforward solution for reconstructing the paintings, but it is not so effortless in our case: the photographs do not cover the whole building but only the places that exhibit paintings. Taking more pictures would not change this situation because the uncovered zones are mainly composed of repetitive patterns and textureless surfaces unsuitable for photogrammetric reconstruction. As obtaining several isolated reconstructions for each painting would considerably complicate the transferring process, we have combined laser reconstruction and photogrammetry. We have used the laser data to generate the geometry model of each site and photogrammetric data to texture the models.

6.1. Data preparation

Photo blending techniques used in the photogrammetric pipeline are sensitive to changes in illumination between images. In contrast, Structure from Motion algorithms, also used in photogrammetry, are not illumination sensitive but require significant overlaps between images to estimate the camera poses. Due to our photographic setup, where we constantly need to move the light sources through the scene, our set of photographs suffered from significant illumination changes between images. Thus, not all the available photographs were usable to compute the models' texture. For this reason, our first step was to perform a manual selection of the images deciding which of them we were going to use in the texture blending step.

After that selection, we processed the photographs using Adobe Lightroom. For the images only used to estimate camera poses, we adjusted white balance and exposure trying to homogenize, as much as possible, the lightness of the images. Besides that, to ensure the accuracy of the colors, we calibrated the images used in the texture blending step as follows. For each subset of images with the same illumination schema, the photographer took an image using an X-rite ColorChecker. So, we computed the ColorChecker ICC profile and applied it to all the images of the subset.

6.2. Photogrammetric process

After testing several photogrammetric solutions, we decided to use Reality Capture because it generated higher quality reconstructions

Figure 6: *Differences in illumination between photographs cause color artifacts (such as light/dark spots) in the painting reconstruction.*

Figure 7: *Illumination correction of the left wall of the window. When we did not have well-exposed images of a small paintings region (left), we locally processed them using Adobe Photoshop to correct exposure (right).*

Figure 8: *The photogrammetric-generated textures are high resolution, less than 1 mm per texel, and allow for the correct reproduction of the paintings for general views (left) and close-up views (right).*

Figure 9: *When the changes in illumination depended on the orientation of the different parts of the surface, we divided the texture into different layers that were later combined to achieve well-exposed textures. The texture layer for windows, arch, and the front wall is shown on the left, while the texture layer for the interior of the apse is shown on the right.*

with our data. However, the photogrammetric process of our data was not as smooth as one could expect, and we needed to deal with some unforeseen issues during it.

First, the software did not always succeed in computing the camera poses or aligning them with the laser scan data. For instance, the camera poses were wrongly estimated or disconnected from the rest when columns hid paintings or when they were too isolated. To solve that, we had to manually place control points in the affected images to guide the computation of the camera poses and the merging of the isolated components.

Once all the camera poses were computed and correctly aligned with the laser scan data, we generated the 3D model of the surface using only the laser data. Besides the typical cleaning process to filter isolated and degenerated triangles, our data needed another cleaning step. As museums exhibit the paintings on mockups of the church building, considerable parts of the captured surface by the laser scan do not exist in the church. To ease the transferring of the paintings to the different church models (see Section 8), we cleaned the models removing the parts of the mockups that do not exist in the church or that differ substantially.

Finally, we generated the photogrammetric textures for each model. First, we parameterized the mesh. The quality and resolution of the photographs are so high that we were able to use a fixed size uv strategy guaranteeing a resolution of 0.179 mm per texel (Figure 8). However, due to the changes in illumination between photographs, texture blending algorithms do not provide satisfying results, and problems with the computation of the color arose. Some regions of the model were visible from different cameras receiving different amounts of irradiance. Consequently, color artifacts appeared in these areas (Figure 6). We dealt with them by following two different strategies. On the one hand, there are parts of the model for which we do not have enough well-exposed photographs due to insufficient captures. In that case, we manually processed the images by increasing the exposure of the dark regions using Adobe Photoshop. Figure 7 shows the images before and after of this process. On the other hand, there are situations when the coverage of the surface is good enough but differences in the surface radiance are significant due to strong changes in the orientation of the surface normal with respect to the positions of the flash lamps. In these situations, we divided the model into different parts depending on the orientation of the surface, and we generated different textures for each of them, considering only the well-exposed photographs. Figure 9 shows the different texture layers generated on the final 3D model. The different textures generated for the same region were blended back together in a later step (see Section 8).

7. Definition of Surface Materials

Since the architecture of the church changed significantly during the different architectural phases, it is not possible to directly use a photogrammetric reconstruction of its current state to texture all the past phases. One possibility could be extracting textures from this reconstruction and using them in previous phases as well. However, this approach has some drawbacks. For instance, the quality of the textures would be limited by the resolution of the captured scans -

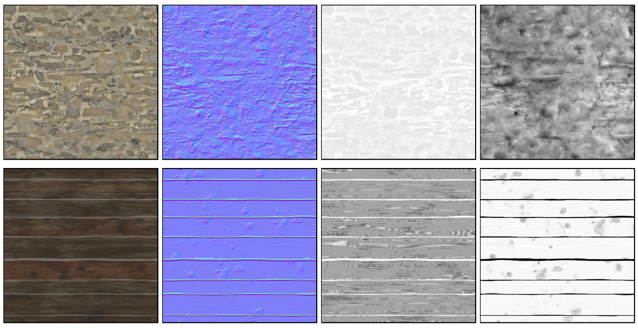

Figure 10: *Examples of generated materials: rock wall and dark wood. From left to right: color, normals, roughness, and displacement channels.*

which is much lower than the pictures of mural paintings - and we would need to estimate other material properties like surface normals, roughness, and displacement maps. Therefore, we decided to generate *procedural materials* that resemble those we can currently observe on-site.

We used Adobe Substance 3D and adapted some of the materials found in their assets library. The generated materials include stone walls, plaster walls, pavements, roof tiles, light and dark wood planks, rocks, and grass. For each material, we exported the color map, normal map, roughness map, alpha map (if applicable), and displacement map. Figure 10 shows some examples of generated materials.

The models and the materials were imported into Blender for texturing. The architectural models from the architects contained an initial labeling about the expected materials type on the objects and surfaces, defined using plain colors. This was manually refined on those cases where we had more than one material for the same label (e.g., we used three different materials for objects marked as 'wall': main walls, plaster walls inside the apses, and columns).

8. Mural painting transfer

Once the models were textured with the appropriate materials, we added the photographs of the mural paintings to the pertinent models and locations, depending on the architectural and pictorial phase. First, the area to be textured in the destination model (e.g. an apse wall) often needed to integrate information from multiple photogrammetric models and/or texture layers. Luckily, in our case, the supports of the paintings exhibited in the two museums reproduce, even with differences, the original architectural structures and spaces. Therefore, we only needed one photogrammetric 3D reconstruction for each space. However, as explained in Section 6, we often needed more than one texture layer to avoid color artifacts. Each of these source layers was transferred independently onto the destination model's texture, and we later blended them all together. Note that this approach would also work for the case of one painting distributed into different museums, thus requiring multiple 3D reconstructions.

Then, we had to transfer the source photogrammetric textures onto the model textures. But this transfer is not straightforward.

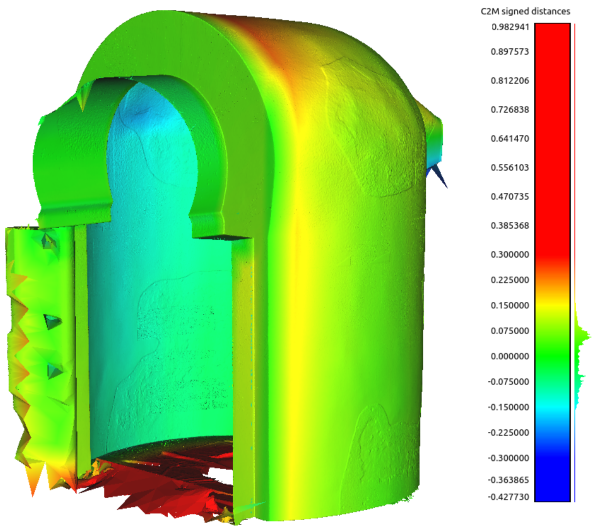

Figure 11: *Deviation (in meters, blue colors corresponding to $\leq -0.3m$ and red ones to $\geq 0.3m$) from the mockup surface, where paintings are currently exhibited, to the reconstructed 3D model. This deviation makes the virtual transferring process of the paintings more challenging.*

Not only for the several texture layers of each space but also for the differences in shape between the source and the destination shapes of the surfaces. Figure 11 shows the distance from the captured mockup of the museum where the paintings are exhibited, to those reconstructed using photogrammetry (see Section 6), to the architectural model where we will transfer them. Note that not only structural elements are affected, but also the parts of the apse that holds the paintings. This issue concerns both the architectural models and the captured church walls. To solve that, our first experiments tried to unwrap the photogrammetric-models geometry into the same texture coordinates as the architectural models. However, given the huge polygon count of these reconstructions - even after simplification - it was impractical to manually control and adjust the unwrapping to ensure a good matching.

Instead, we decided to project the color from the photogrammetric model onto the architectural one, storing this projection directly in its texture layers with the proper texture coordinates. Note that photogrammetric reconstructions are not necessarily in the same coordinates as the architectural models, thus we need to align them. To do so, after a first rough alignment through a few user-defined corresponding point pairs, we used the Iterative Closest Point (ICP) algorithm [BM] to find the transformation that better aligned both models. We kept the coordinates of the architectural model fixed, such that the transformation matrix was applied only to the reconstruction. Since the geometry of the models is not exactly the same, we often needed a manual refinement of the alignment after ICP. Finally, we used a ray casting algorithm to project the image from the source photogrammetric textures to the destination model textures (Figure 12).

Figure 12: *Top: the architectural model (left) and the photogrammetric model (center) are aligned using ICP (right). The bottom image shows the result of transferring the paintings onto the procedurally textured model.*

After repeating the previous alignment and raycasting for all source models and layers, we obtained the composite picture of the paintings in the architectural model's texture space. Finally, we blended the paintings' texture with the procedural material texture. We decided to keep a small band around the paintings, mimicking the borders produced during the *strappo* process.

9. Results and discussion

We obtained five different models representing the architectural and pictorial evolution from the 9^{th} to the 13^{th} centuries. The complexity of each model geometry ranges from 11k faces for the simplest one (9^{th} century) to 30k in the largest (12^{th} century). However, our methodology is also valid for more complex models. The maximum texture resolution could be limited by that of the photogrammetric textures since the procedural materials can be baked into any desired resolution. In our case, for the museum exhibition, we exported 32 texture atlases at 8192×8192 resolution: 12 color maps, 10 roughness maps, and 10 normal maps (note that, in some cases, only the paintings changed so we could reuse roughness and normal maps of the underlying material). Areas with paintings were allocated relative sizes in the atlas 8 to 16 times larger than non-painted walls. The total size of exported models and textures was 2.17GB.

The architectural evolution of the church can be seen in Figure 13, which shows an exterior view of the final models. Note that we did not include an exterior render for the 12^{th} century since the architecture did not change from the previous one. The pictorial evolution is partly shown in 14, rendering a view from inside the central nave towards the central apse. Note the first paintings appearing in the central apse during the 11^{th} century, then changed and expanded in the 12^{th}, before being partially covered by the thicker walls in the 13^{th}.

Figure 16 shows another view of the 12^{th} century nave, demonstrating the integration of the procedural materials with the paintings photographed from the three physical locations. Figure 17 shows a detailed render of one painting, with procedural plaster material on the walls.

Overall, this project shows how to reconstruct, in a single model, the church of *Sant Quirze de Pedret* and its dispersed mural paintings. This reconstruction benefited from multidisciplinary research, including archaeology, art history, and architecture, which allowed us to model and texture the church at different significant historical moments based on the known evidence. Moreover, we have presented an acquisition methodology that can guarantee a correct representation of the mural paintings with a consistent illumination through the whole church, thanks to an acquisition schema using portable lighting equipment, a later illumination correction procedure, and the use of different texture layers. Besides that, our methodology includes a texture transferring process that allows us to bring the currently dispersed mural paintings back together into a unique virtual model without visible deformations. Although we have shown this transfer from the mockups of the museums to the architectural models, our methodology will also work by transferring the paintings to the captured walls of the church, as the shape differences between mockups and church surfaces are even lower.

Our final models are suitable for multimedia works, interactive visualizations in real-time, and virtual reality applications (the latter adjusting the resolution of the textures). They result in valuable data for experts and visitors. Recovering the integrity of the paintings can help, on the one hand, the art historian researchers to better understand the relations between different fragments of the mural paintings currently separated and, thus, improve their interpretation. On the other hand, having the chance of seeing the whole monument in a virtual recreation helps the visitors to understand the fragments of the real paintings in front of their eyes. For this reason, MDCS, in its recent refurbishment (see Figure 15), has included our models in an audiovisual work projected on a big screen next to the paintings they hold to improve the visitors' experience. See the accompanying video.

10. Conclusions

In this paper, we have presented the case study of Sant Quirze de Pedret: an example of a 3D reconstruction of a monument, currently split and exhibited in different locations, that takes into account the architectural phases of the different significant moments of the monument. Our work has focused on church building reconstruction in different historical moments, the virtual reproduction of the materials present in the church, the 3D reconstruction of the preserved paintings, and its transfer to its specific location on the church building. Besides the results of this project, it shows an illustrative example of the reconstruction of historical buildings and their changes over time. Moreover, it also presents a methodology for the reconstruction of paintings dispersed among several locations, with challenging illumination conditions, and their gathering by virtually transferring them to their original location. As

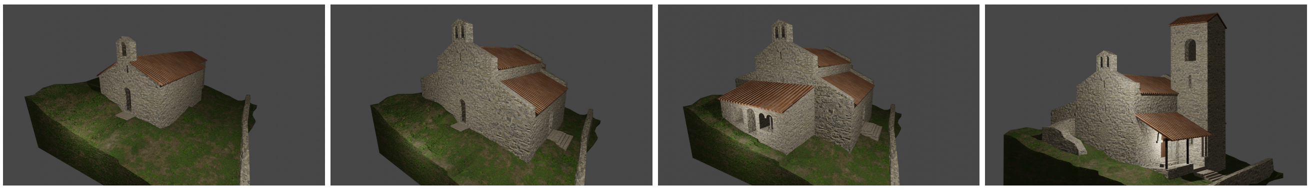

Figure 13: *Renders of the final models showing the evolution of the exterior in the* 9^{th}, 10^{th}, 11^{th} *and* 13^{th} *centuries.*

Figure 14: *Renders of the final models showing the evolution of the central nave in the* 9^{th}, 10^{th}, 11^{th}, 12^{th} *and* 13^{th} *centuries.*

Figure 15: *Inauguration of the refurbishment of the Sant Quirze de Pedret room in MDCS: the new screen, one of the main improvements of the refurbishment, shows an audiovisual created using our models. Museu Diocesà i Comarcal de Solsona, May 19th, 2022. [MDC22]*

future work, we would like to incorporate virtual reconstruction techniques (such as color restoration and the incorporation of virtual drawings) to enhance the paintings and their state of preservation. Moreover, we would like to improve the rendering realism considering on-site captured illumination. In conclusion, it is possible to overcome the historical situations that affect the integrity of a monument by gathering back its parts while, at the same time, taking into account its historical evolution. Sant Quirze de Pedret is an illustrative example of this.

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Figure 16: *Sample render of the final model for the* 12^{th} *century, viewed from the central nave.*

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Figure 17: *Detailed render showing paintings and procedural materials.*

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