Portalada: A Virtual Reconstruction of the Entrance of the Ripoll Monastery

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Abstract

The dichotomy between detail representation and data management is still a big issue in the context of the acquisition and visualization of 3D objects, especially in the field of Cultural Heritage. New technologies give the possibility to acquire very detailed geometry, but very often it's very hard to process the amount of data produced. In this paper we present a project which aimed at virtually reconstructing the impressive (7x11 m.) portal of the Ripoll Monastery, Spain. The monument was acquired using triangulation laser scanning technology, producing a dataset of more than 2000 range maps for a total of more than 1 billion triangles. All the steps of the entire project are described, from the acquisition planning to the final setup for the dissemination to the public. In particular, we show how time-of-flight laser scanning data can be used to obtain a speed up in the alignment process, and how, after model creation and imperfections repairing, an interactive and immersive setup gives the public the possibility to navigate and visualize the high detail representation of the portal. This paper shows that, after careful planning and with the aim of new algorithms, it's now possible to preserve and visualize the highly detailed information provided by triangulation laser scanning also for very large surfaces.

1. Introduction

The Benedictinian monastery of Ripoll was founded by count Guifré el Pilós in 879. The main work of art from the monastery, which is also the main Romanic sculpture from Catalonia, is the entrance (known as **Portalada**), which dates back to the 12th century. This entrance has been defined as the "Stone Bible". It is a masterpiece of cultural, historical, social and scientific interest. Ripoll is located 90 Km North from Barcelona, quite apart from the main tourist routes. It was necessary to find novel approaches to show this impressive monument to the visitors in Barcelona and disseminate its contents to a wider audience. This motivation, together with the deterioration of the stone, was a strong argument for romanic experts and museum curators at the Museu Nacional d'Art de Catalunya (MNAC) in Barcelona to ask for a virtual model of this significant cultural heritage masterpiece.

This paper presents the project of the virtual reconstruction and presentation of the Portalada monument, which produced an interactive installation which is currently available to the public in the MNAC exhibition named "The Romanic Art and the Mediterraneum. Catalonia, Toulouse and Pisa" from February to May 2008.

Visitors to the exhibition can interact with the virtual reproduction in two different immersive setups (VR kiosks). Using a touch-screen and a back-projection display screen with passive stereo, visitors can simply navigate and zoom-in different parts of the entrance, or they can get further information just by touching different "hotspots", which make 3D information boards appear in front of important components of the facade (see Section 5). They can for instance discover a representation of Moses leading his people or notice that little stone carvings represent the labors associated to every month of the year. The stereo immersion and the shading model help in creating a more realistic perception of the volume and of the true aspect of the stone figures in a way that enhances the realism of the user experience.

The project challenges derive from the museum requirements. The goal of the project is three-fold: having a high-fidelity virtual reproduction for the exhibition, creating a tool for the study and analysis by the experts, and allowing the archival of the present status of the Monastery entrance. The main contributions of the paper are tightly related to the processing and real-time managing of the gigantic mesh representing the Portalada. They include,

- The acquisition and model construction process which, given the very large sculpted surface (7 x 11 meters), produced a nearly complete 173M faces high resolution model, with a sampling density of the order of one millimeter..

- The derivation of specific scalable algorithms for model repair and simplification
- The design of a hierarchical data structure for data managing and view-dependent navigation
- The setup of a usable, user-friendly and immersive system that induces a presence perception in the visitors.

The work is based on a number of previous works that are listed in the next Sections. The project relies on several hot topics in computer graphics, like model acquisition in Cultural Heritage Applications, geometry processing algorithms for model repair and simplification, view-dependent visualization and gigantic models handling algorithms.

Details on the acquisition process are described in the next Section, while Section 3 presents the strategy for the model construction, including alignment, initial repair and color assignment. Section 4 presents the main repair process and the algorithms and data structures for view-dependent visualization. Then, Section 5 describes the interface and the layout and structure of the virtual reality kiosks. Finally, Section 6 discusses the overall process, presenting the conclusions.

2. Acquisition

The Portalada of Ripoll is an incredibly rich monument: every single section tells a story, sacred and profane mix continuously throughout its surface. For this reason, the acquisition of the portal needed a particular care in the preservation of detail. Time-of-flight scanning industry provided, especially in the last few years, new devices which give the chance to acquire very large surfaces in a short time and with sufficient precision. However, triangulation laser scanners still provide sub-millimetric sampling density acquisition and higher accuracy.
In the case of Portalada the study of a single statue or bas-relief can be the topic of the work of an art historian for several years. Moreover, most of the single statues and bas-relieves present small details, which can be very important for their artistic and historical message. For these reasons, it was decided to use triangulation scanning, with the aim of having a inter-sampling density of at least 1mm. Since performing a triangulation-based scanning of such a huge carved surface (7x11 meters) was very challenging (difficulty in covering all the surface, complexity in registration step, etc.), we decided to run a double acquisition, using both technologies. Several previous projects in the field of Cultural Heritage presented a mix of lower detail models (obtained with time-of-flight scanning, 3D modeling or photogrammetry) of large areas and triangulation-based scanning of more detailed areas [14, 17, 3]. In our case, we planned to do a complete double scanning of the same surface and an integration of the two data sources.
The reasons behind this choice were several:

Time Of Flight scanning Campaign	
Scanner model	Leica ScanStation
Acquisition Time	1 day
N. of stations for Portalada	3
N. of stations for Exterior	1
Acquisition Resolution (Portalada)	0.5 cm
N. of points acquired (Portalada)	36.2M

Table 1. Time Of Flight Acquisition Data

- The area covered by a single range map acquired with a triangulation scanner is usually not bigger than 50x50 cm. Consequently, several hundreds range maps were needed to cover the entire surface. The accumulation of the alignment errors could have resulted in difficulties for the global alignment of all the range maps. Moreover, the accumulation could have led to a slightly deformed final model. The use of the time-of-flight scanned model as a reference for alignment (see Sect. 3) solved both these issues.
- The technical constraints of the triangulation scanner (acquisition distance between 50 and 150 cm, small area covered by each shot) result in difficulties in having a complete sampling of such a large object. The different point of view and more consistent coverage of a time-of-flight scanning could provide more information and cover parts which could not be acquired by the triangulation scanning.
- A low resolution scanning of the area around Portalada could be a good data set to visually describe the current position of the monument.

Tables 1 and 2 present some numerical data regarding the acquisition campaigns. The Time of Flight scanning (Table 1) was performed by a team of 2 technicians using a Leica ScanStation. It took 1 day of work and 4 acquisition stations to acquire data of both the Portalada and the exterior monastery facade. The Portalada was scanned at a resolution of 0.5 cm, providing a data set of 36.2 Million points.

The triangulation-based scanning was performed in 5 days by a team of 4 people using 2 Minolta Vivid 910 scanners. During the acquisition planning the monument was subdivided in 62 overlapping sub-sections (the acquisition planning schemes for the frontal part of the portal is shown

Triangulation scanning Campaign	
Scanners model	Minolta Vivid 910
Acquisition Time	5 days
N. of sub-sections	62
N. of acquired range maps	2212
N. of points acquired	500 millions

Table 2. Triangulation Acquisition Data

in Figure 1). Each sub-section was acquired with a number of range maps varying from 20 to 90, depending on the size and complexity of the geometry. In order to be able to scan the upper part of the portal, a movable 7 meters tall scaffolding plus a smaller one were used (Figure 2). The final data set was composed by 2212 range maps and more than half a Billion samples acquired.

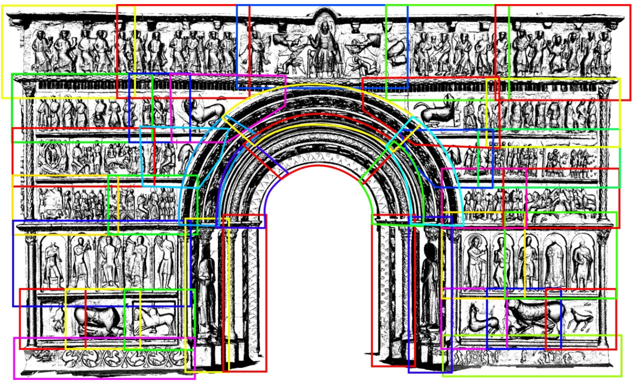

Figure 1. The planning scheme used to scan the Portalada with the triangulation-based technology: each box correspond to a subsection acquired

Finally, more than 200 photos were taken to document the acquisition campaign and cover the entire surface for color projection (see Section 3.4).

3. Model Generation

In this section we present a description of the work that has to be done to generate a model from the acquired data. Several issues raised in this phase, especially during the alignment operation, described in Subsection 3.2.

3.1. Time of Flight model

Only a number of local tests to check the quality and completeness (as far it is possible on a set of two thousand range maps) were carried out on the field. Once back in the lab, the first data processed were the TOF scans.

Figure 2. Left: the 7 meter high scaffolding used for acquisition. Right: a smaller scaffolding used for the acquisition of the internal part of the portal

Thanks to the alignment provided by the reference markers used during the scanning, the three scans were already perfectly aligned: only some filtering and cleaning of the data was needed. The three scans were merged at different resolutions (1cm and 5mm), in order to obtain models with a good level of detail, but easy to manipulate.

The TOF models were used several times in the course of processing for the initial assessment of the data, both for visual reference in the alignment process and for work organization. They were used to perform the initial alignment of the photographic dataset, in order to assess the completeness and quality of the photographic information while the hi-resolution model was still under processing.

However, the most important use of the TOF model was the geometrical reference during the alignment of the triangulation range maps, as explained in the next section.

3.2. Alignment

During the acquisition, the surface of the Portalada was divided in different subparts, as shown in Figure 1. The subdivision was performed trying to follow the original structure of the artifact, which is divided in several “scenes”. Each of these subparts were acquired independently, mainly for two reasons: since moving the scaffolding was quite cumbersome, it was only possible to work on a small area at a time; moreover, having smaller but contained and significative subparts greatly helped the organization of the data processing.

Each subpart of the Portalada was acquired following a regular coverage pattern, with consistent overlap between adjacent range maps. This regularity gave the possibility to employ automatic approaches [11] for initial alignment of the range maps. This resulted in a speed up the alignment process during data processing.

After this first rough registration, the standard ICP-based fine alignment was applied to each subpart in order to obtain a good alignment [6]. The overall alignment of the subsections, which was the operation which needed the higher amount of human intervention, was nearly 10 days. At this point, each subpart of the Portalada was ready to be merged; however, we were interested in building a single model for the entire portal. It was then necessary to find a way to integrate all the range maps in a single reference space.

Each subpart contained a "border" of about 20-30 cm that was shared with its neighbors subparts. In principle, by using this overlap it should have been possible to use the standard alignment procedure between adjacent subparts and obtain a global positioning for all the range maps. Since it was not possible to calculate global alignment on a group of more than 2000 range maps, we merged some of the subparts and we aligned the resulting merged models, in order to obtain the spatial relationship between subparts. We then applied the obtained transformations to the original range maps and we merged them together. This solution proved to be ineffective: although each subpart was correctly aligned, the alignment error accumulated on the borders, thus deforming the overlapped area and resulting in a subpart-to-subpart imprecise alignment.

It was then clear that, to produce a valid result, we needed a way to apply alignment at multiple *levels*: subpart, border and whole object. In particular, we were concerned about the deformation that could occur while aligning an object of such extent using range maps that, in proportion, were really small. Indeed, the global alignment step [12] helps distributing the alignment error among all alignment arcs, but it works effectively only if the object is a "closed" surface, while it does not guarantee to eliminate all error accumulation if the surface has large, open borders. The Portalada was a clear example of this situation. Given the lack of the posterior part of the artifact and the relative small size of range maps with respect to the entire object, we were sure that a standard alignment process would have led to severe deformations.

We overcome this issue by using the model obtained by the Time of Flight scanning. Since each TOF scan contained the entire extent of the Portalada, the resulting model could be used as an alignment reference, in order to obtain a rigid global alignment. Using the TOF model, we were able to build an alignment process that proved to be viable in terms of required time and human intervention but, more importantly, to provide accurate results. The first step was to place all subparts in the correct position; each subpart was hand-positioned on the TOF model using an alignment software and then a step of ICP was performed to obtain a good positioning. By applying the roto-translation of each subpart to all its range maps, we automatically placed all the maps in the global reference space. However, since at this point we did not consider cross-alignment between range maps of different subparts, there were still misalignments in the border areas between different subparts. To avoid this problem, we then loaded different sets of adjacent subparts and performed a global alignment for range maps in the border.

The entire alignment process was composed of three different steps, iterated several times in order to guarantee a stable and accurate final alignment.

- alignment between range maps inside each subpart
- alignment step of range maps of a single subpart toward the TOF model
- alignment between range maps of adjacent subparts

Basically, what we did can be considered a *manual, out-of-core, multiscale* global alignment step. The standard alignment tools, both commercial and academic, are designed to work on datasets that are smaller than the one produced in this project. Since in our case it is was impossible to directly manage the entire range map dataset in our alignment tool, it was necessary to define an alignment pipeline with a lot of data swapping and manual organization of work. Experience shows that each large-scale project has some specific constrains and characteristics that make it unique. For this reason, writing a specific program to cope with such singularity may be not a good choice (it was also not possible in the case of the Portalada scanning due to the time pressure: acquisition and processing have been performed in just seven weeks). A better solution to avoid the manual intervention would be to extend the existing alignment tools to be script-ready. In this way it would be possible to use the basic alignment operations (pair/group alignment, global optimization) *parametrically*, adapting the process to the specific needs of the project.

3.3. Reconstruction

After generating a correct alignment for all the range maps, the next step was to create a single surface for the entire object. We used a merging tool which adopts a standard volumetric algorithm based on distance fields. Obviously, given the size of the dataset, the reconstruction was carried out by dividing the object bounding box in various parts and working on each component separately. The resulting pieces were then put together, and the replicated border vertices were eliminated, thanks to a specific feature of the out-of-core reconstruction code [6].

Even if this dataset was the biggest we ever worked on, it was not one of the most difficult for merging. This was due to the ”flat” nature of the surface and the small extent of each range map: each part of the object was covered at most by five or six range maps. Since the reconstruction is mostly carried out using local data, all the needed information easily fitted in memory. In order to speedup this step, the merging was simultaneously performed on multiple machines. The total merging time required was 26 hours. The merging produced 406 separate blocks, for a total size of 170M triangles and 3.5 gigabytes

Actually, the merging process was performed several times, in order to spot local misalignments and uncovered areas. Some small misalignments still remained since, given the dataset size and the multistep alignment process, it was impossible to completely check every area of the object. Those alignment problems became apparent in the merging phase and were corrected by manually finding the out-of-place range maps and recalculating the alignment in that specific area. The impossibility to reach some of parts of the surface with the triangulation scanner resulted in small uncovered areas. This lack of data was clearly visible in some low detail areas of the middle arch and in some difficult-to-reach parts on high-reliefs. We were happy to find that no major holes were present in the important and detailed areas. The missing parts were filled by carefully cutting small areas from the TOF range scans. The merging tool was also configured to use for this kind of data only when no other data were available. The result was a seamless integration of the missing area, with minimal quality degradation. The production of the final model took a further week of work, but needed human intervention was in this case very limited.

3.4. Color management

Once the geometry of the portal was reconstructed, the following step was to associate the color information to the geometry of the model. This is usually done by registering a set of images on the model, and projecting the color values on it. In this particular case, due to the size of the portal and the peculiar lighting conditions, the acquisition of images was quite hard, and it resulted in a set of almost 200 photographs.
Also in this case the scaffolding was used, and the acquisition was performed trying to be in the best and constant lighting condition. After the image-to-geometry registration process [9], 163 images were projected on the geometry, by associating a color value to each vertex of the model [5]. The unavoidable differences (illumination, resolution...) between the photos were blended, obtaining a generally satisfying result. Snapshots of details of the final colored model are shown in Figure 3.

Figure 3. Two snapshots of details of the colored model of Portalada

4. Model Processing and Realtime Visualization

Starting from the raw model produced in the previous phase, the geometric processing of the Portalada model involved a first repairing step, followed by the creation of the multiresolution model and of the in-core octree data structure.

Model repair is a hot research topic (see for instance [4]) in which a good number of recent algorithms have been proposed. The main problem in our case was, once again, the huge amount of data. Apart from detecting and repairing small imperfections (ill-oriented triangles, noise, spurious polygons) we had more than 25000 small holes to repair. Holes and cracks were automatically detected through a search for cycles of border edges. Instead of using standard approaches like [7], we decided to implement a multigrid version of the fitting and smoothing loop proposed in [8]. The goal was to obtain a single mesh without border edges.

The hole filling algorithm works as follows: for every detected cycle of border edges, we first compute its bounding box. Left of Figure 4 shows one of the holes in the original geometry. A first approximating surface that covers the hole area is initially computed in a similar way as in [7], but using a coarse voxelization of the bounding box. This is an implicit surface, being the zero isosurface of a four-dimensional functional B-Spline defined on the voxelization domain. Then, the algorithm iterates in a multigrid way by performing the three following operations in each of the iterations:

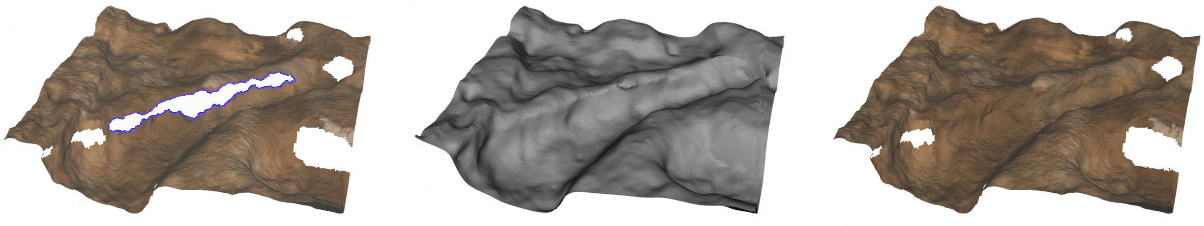

Figure 4. The model repairing process. Left: the original geometry with the working hole highlighted; Center: the hole filling surface, computed on a reduced voxelization; Right: the closing surface has been integrated in the full resolution model

- The voxelization is refined by splitting each voxel in its eight octants. The new approximating surface can be easily computed by using the classical subdivision algorithm of uniform B-Splines.
- The fitting algorithm from [8] is used in order to push the approximating surface to the centers of the new voxels that contain mesh triangles. This is a least-squares algorithm that tries to force the isosurface to interpolate all voxel centers.
- A smoothing step is performed in order to improve the fairness of the shape of the approximating surface. The goal of this step is to minimize the jumps of the third derivatives between neighbor voxels. Details can be found in [8].

The final approximating surface for the example in Figure 4 (left) is shown in Figure 4 (center). This approximating surface is used to compute Steiner points (3D points inside the hole) that are used to triangulate and produce the necessary new triangles inside the hole. The result, once the central hole has been repaired, can be observed in Figure 4 (right). This process is iterated over each hole of the original geometry. The final repaired mesh has 173 millions of triangles, with an average edge length of 1.4 millimeters.

The next step was the generation of a low-resolution textured base mesh, with 200K triangles. Textures were obtained by projecting points of the high resolution mesh onto the 3D points of the low-resolution triangles that correspond to each of their texels, following the algorithms in [16]. Color textures and normal maps were encoded on a texture Atlas, the size of the Atlas being 600 MBytes.

In our present implementation, we observed that it was possible to obtain a high visual quality by using a three-level multiresolution model. The model works as follows: at observer locations that are farther away than 2 meters, we simply render the textured base mesh (which is permanently located in the memory of the GPU through a number of vertex buffer objects). For intermediate distances, we use a relief impostor [2] based representation, see [1]. For close-up views (distance lower than one meter), we render the high resolution mesh. This high-resolution mesh has been splitted in submeshes of around 60 K triangles each, in order to optimize the performance of the CPU and GPU caches. All triangles of the high-resolution mesh are univocally assigned to one of the submeshes, but border vertices are duplicated in neighbor submeshes.

We have designed a hierarchical data structure management of the multiresolution meshes. In a preprocess step, we compute an octree that represents a hierarchical linear distance field [15] which approximates the distance from the observer to the portalada: each octree node stores a base distance and the gradient of the distance field. During octree construction, the maximum deviation between the linear approximation of the distance and the exact distance to the portalada is computed for the node being processed. It this deviation exceeds a predefined tolerance, the node is subdivided and the distance gradient is computed for each of its son nodes. Octree nodes also contain pointers to the portalada models (relief impostors or high-resolution submeshes in the leaf nodes). Some leaf nodes have also pointers to information files (text or images). The octree data structure is permanently in-core during the navigation. In our present implementation, the number of leaf nodes containing parts of the mesh is 280000. The depth of the octree is 10 levels, giving an edge size of 3.51 centimeters for a Universe size of 18 x 18 x 18 meters.

The interactive visualization uses a view-dependent algorithm (see [13], [10]). An octree traversal is performed at each frame to first detect if the movement of the observer is valid or not. In the affirmative case (the observer is not exiting the octree Universe and his distance to the surface of the portalada is greater than 30 centimeters), the view-dependent front is obtained (based on the size of the projection of the cube nodes in pixel coordinates), and the list of models that should be rendered is computed. This is based on the distance between the observer and the surface of the portalada, as computed by the hierarchical linear distance field. The octree traversal is also used for hierarchical frustum culling and for the generation of the list of visible submeshes for the present frame. Each visible submesh inside the frustum is assigned a priority which is related to the distance of its projection to the center of the viewport. The rendering algorithm uses CPU and GPU cache storages. A lazy CPU-GPU communication algorithm is used, where a single mesh per frame is sent from the CPU to the GPU: the one having the highest priority in the CPU list, among the ones still not being sent. We use a fragment program that implements shading and shadow algorithms.

5. Interface and Immersive Inspection

Since the goal of the visualization system was to give access to the extremely detailed fidelity of the digital model, it was mandatory that the presentation system allowed the visitors to navigate and zoom-in very close to any part of this monument. Exploiting this freedom of movement, visitors will be able to inspect hidden and unreachable details that cannot be seen by people going to the actual monument in Ripoll, because they are located at 6-7 meters from the floor. Moreover, users will be able to retrieve pictures, texts and views of destroyed parts of some of the sculptures that cover the whole portico. The final exhibition stand presents two immersive kiosks. Interaction is performed through a touch-screen, see Figure 5. Visitors interact with the touch-screen, using the arrows to get closer or farther away, and moving the frame along the facade to produce a pan effect. The virtual movement of the track ball rotates the camera. The shape of the frame changes with this rotation, so that it always encloses the portion of the monument that is displayed on the immersive screen. An informal usability test was performed on a group of ten persons, to tune some involved parameters like sensibility of the touch screen and speed and acceleration of the camera changes. The set up for navigating the model allows for different modes of navigation through a specific *mode* button. The zoom, pan and rotation buttons in the touchscreen allow a simple and direct inspection of the Portalada. A second mode pops up further information just by touching different “hotspots” appearing in front of important components of the facade. 3D Boards with pictures from the XIXth century showing missing parts of sculptures or information texts, are displayed in front of the Portalada model. It is also possible to recreate precise sun illumination conditions and, by using a “virtual flashlight”, the viewer can produce sharp and very precise shadows with stone grain precision that helps in creating a more real perception of the volume and of the true aspect of the stone figures.

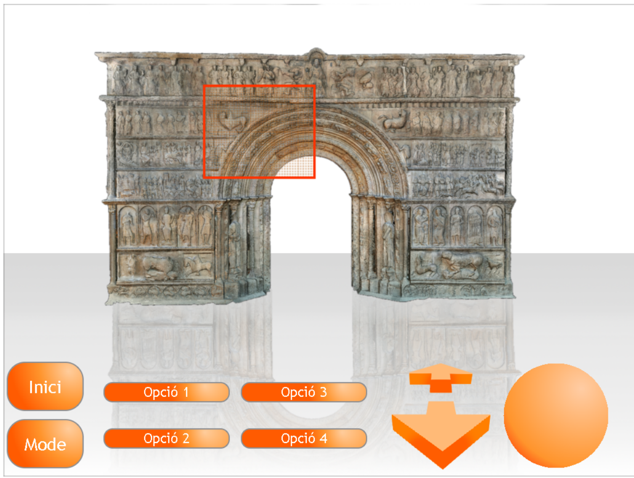

Figure 5. The interface of the touch-screen that controls the kiosk

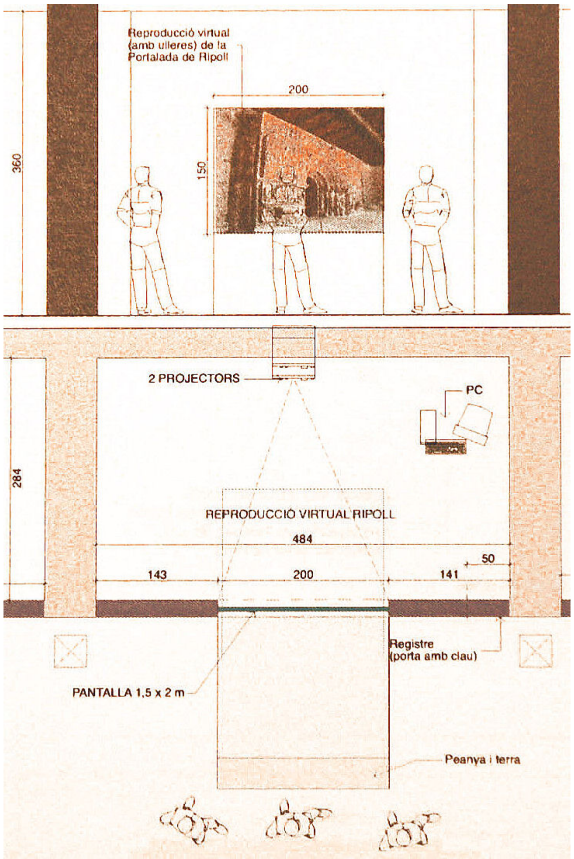

Figure 6. Design of the layout of the interactive kiosk of the exposition

The layout of the VR kiosks is presented in Figure 6. Each kiosk consists of a back-projection display with two projectors and passive stereo, and a touch-screen. Each kiosk includes two PCs, linked in a LAN. One of them is devoted to the stereo rendering and to the handling of the view-dependent visualization and model managing. The second one controls the interface, computes lighting directions and updates the position and shape of the frame on the picture of the Portalada.

6. Conclusions

In this paper, we have presented the project of the virtual reconstruction of the entrance of the Ripoll monastery in Catalonia, Spain. The project is the result of a successful cooperation among the MNAC museum, UPC in Barcelona and ISTI-CNR in Pisa. The project has involved a number of important challenges, going from the size of the portalada and the quality and precision requirements to the extremely tight schedule: the whole project had to be finished within a period of 4 months.

The acquisition process and the alignment for the generation of the high resolution triangles mesh involved the use of novel techniques that, according to our knowledge, have never been used before. Specific scalable algorithms were designed for model repair and simplification, and a suitable octree data structure was designed for data managing and view-dependent navigation. A user-friendly interface was designed for the two immersive, passive stereo VR kiosks. In the whole process, the huge sampled dataset has been transformed into a valid mesh of triangles with millimetric resolution, that can now be inspected in real time in the PC-driven kiosks. The informal evaluation by the museum visitors is highly positive.

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