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VR-assisted Architectural Design in a Heritage Site: the Sagrada Família Case Study

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Abstract

Virtual Reality (VR) simulations have long been proposed to allow users to explore both yet-to-built buildings in architectural design, and ancient, remote or disappeared buildings in cultural heritage. In this paper we describe an on-going VR project on an UNESCO World Heritage Site that simultaneously addresses both scenarios: supporting architects in the task of designing the remaining parts of a large unfinished building, and simulating existing parts that define the environment that new designs must conform to. The main challenge for the team of architects is to advance towards the project completion being faithful to the original Gaudí's project, since many plans, drawings and plaster models were lost. We analyze the main requirements for collaborative architectural design in such a unique scenario, describe the main technical challenges, and discuss the lessons learned after one year of use of the system.

CCS Concepts

•***Computing methodologies*** → *Virtual reality;* •***Human-centered computing*** → *Collaborative interaction;* •***Applied computing*** → *Computer-aided design;*

1. Introduction

The Expiatory Temple of the Sagrada Família is one of the most visited temples in the world and the only one still under construction. The first architect was Francisco de Paula del Villar who started the construction in 1882. A short while later, he resigned and Antoni Gaudí took over in 1883. Gaudí proposed abandoning the original Neogothic plan in favour of a design that was more monumental and innovative, in terms of form, structure and construction. Gaudí's designs were inspired by nature and he was interested in more efficient designs that could still be possible to build with the existing technology. Gaudí died in a tram accident in 1926, leaving behind only one finished tower of the Nativity facade and a large number of scale models, drawings, designs, sculptures and photographs.

After Gaudí's death, many other architects have taken over the management of the works, following the drawings and models that Gaudí had created. The construction was severally affected during the 1936 riots. The crypt was set on fire, the studio workshop was destroyed, and a large amount of material (plans, drawings, photographs, and large-scale plaster models) was lost or broken.

In 1939 the construction continued always following Gaudí's concepts and design ideas (a large amount of effort was put into recovering lost pieces and drawings, and reconstructing broken models). Currently, about 70% of the Basilica is finished, while six central towers still remain to be built. The Tower of Jesus Christ will be the tallest, at 172.5 metres. The Nativity facade and the crypt of the Expiatory Temple of the Sagrada Família were inscribed on the UNESCO World Heritage List in 2005.

Over the years, construction techniques have changed massively, and new technology has been needed to turn Gaudí's drawings into architecture (using even aerospace software to turn his complex shapes into reality). Virtual Reality has turned out to be a powerful complementary tool to traditional visualization tools (e.g. 3D scene renders), allowing architects to become immerse in 3D spaces with singular size and shapes. The Project Department is currently using VR in specific parts of the temple. Although the use of VR in the Sagrada Família is not systematic nor global, it has been found to be a convenient companion of 3D modeling tools, whose introduction in the project supposed a great technological advance. Combined with the other technological applications currently used, VR offers a valuable tool for testing new design ideas an evaluating their impact.

Architects create alternative designs for the different buildings parts using 3D CAD software. Often these models are built as miniature replicas (using 3D printers) and from that set of models a few are created in their final size using plaster. Those models would then be installed in their final position within the building, and architects would then spend days or even months looking at the models from different parts of the temple or the streets around the temple. When the architects first considered the use of Virtual

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Figure 1: *Architect evaluating the inside of one of the towers using a HMD.*

Reality, they converted their models from the 3D CAD software to a VR-friendly format, but in this process they were loosing relevant information regarding for example types of stones used or properties of each face of the stones. Then a high quality model for visualization in immersive VR was created by hand by an external provider that assigned materials and optimized the geometry. Besides the economical cost and long time required in this process, the biggest limitation was the poor flexibility of such a workflow. Any small change required to start all over again, due to the manual and uni-directional nature of the pipeline. The limitations above motivated this project: to achieve a fully automatic pipeline from 3D CAD models to real-time inspection of fully-featured models (materials, textures) in a VR headset.

In this paper we describe the on-going VR project that assists architects in the design of remaining parts of the Sagrada Família. In particular, the project so far has focused on facilitating the review and comparison of alternative designs, both in terms of shape and material. It is important to highlight that the final users of this project are the architects, and thus all the different tools developed to export/import geometry and to interact with the model, have been designed following the architects specifications. For example, there are different navigation modes including walk-thorough, free fly-through (ignoring collision detection), and teleportation to predefined viewpoints.

Architects have been using this tool in progress for over a year to evaluate the visual effect and predict user experience to take design decisions both at local scale (e.g. a handrail in a staircase) and global scale (e.g. the visual impact of a particular part of the temple), mostly for the yet-to-be-raised Jesus Christ Tower. Figure 1 shows an architect exploring the aforementioned tower using an HMD.

2. Previous work

VR and AR for cultural heritage Virtual and Augmented reality have been used for several decades to enhance the experience of visiting historic sites [MCB*14, MTP05]. For example, the work by Magnenat-Thalmann and Papagiannakis presented a lively reconstruction of the ancient city of Pompeii by adding animated virtual humans [MTP05]. For recent surveys on the use of VR and AR for cultural heritage we refer the reader to [IMTP17, BPF*18].

VR-based architectural design Architectural design has long been a major application of VR, and immersive technologies have been proposed as a useful tool for architects and designers in nearly all architectural design phases, including schematic design, design development, presentation and evaluation, and detail development [CW94, SWKM95, DR99, AEI03, Why03].

Campbell and Wells [CW94] early discussed the pros and cons of VR in the architectural design process. Despite using primitive VR hardware, the authors found that the VR simulation did provide a way to detect flaws in the CAD model, allowing to evaluate design elements such as proportion, scale, and order that were not immediately apparent in conventional displays. Immersive VR was found to offer the designer a better perception of space and the opportunity to see the design from the inside.

Donath et al. [DR99] described the underlying strengths of VR for architectural design reviews. According to the authors, a major benefit of immersive VR systems is that they allow both egocentric (first person view) and exocentric (bird's view) views of the model. This is possible thanks to the use to head tracking, which allows viewpoint motion to match physical motion (egomotion) to deliver full egocentric frame cues.

Although a key benefit of VR systems for architecture is the possibility to explore the model at 1:1 scale, some VR applications for conceptual design in architecture feature the ability to work in more than one scale simultaneously [AEI03].

Bullinger et al. [BBWB10] discuss how architectural planning can benefit from immersive VR by taking into account the entire life cycle of a building and the different stakeholders including end users, contractors, architects and engineers. The authors observed VR technologies were well accepted by all the participants and positively influenced planning quality, although a major issue was data exchange between tools, which is mostly unidirectional and carries a high error risk due to the different formats used.

Two major open issues refer to the VR system being able to provide (a) enough visual quality and (b) spatially correct perception, to make correct decisions [BBWB10]. These issues have been the subject of a number of studies.

Numerous studies have shown that distances appear to be compressed in virtual environments [RVH13, KTDH15] although the factors that are responsible for this phenomenon remain largely unidentified [IRA06]. Recent studies though have found that distance perception appears not to be significantly compressed in the VR world under some circumstances. Interrante et al. [IRA06, IRL*08] found no significant size compression provided that the high-fidelity, low-latency, immersive VR headset showed an exact virtual replica of the participant's concurrently occupied real environment. Furthermore, Steinicke et al. [SBH*09] have shown that when users start their VR experience in such a virtual replica and then gradually transition to a different VE, their sense of presence and distance estimation skills increase significantly. Architectural design reviews in on-going works (as in our case) can benefit from this finding, since the virtual replica serves as a transitional environment between the real (already built) and virtual world, provided that the VR setup can be placed near the target location. Mohler et al. [MCRTB10] also found that participants who explored the virtual environment while seeing a fully-articulated and tracked visual representation of themselves made more accurate judgments of absolute egocentric distances than did participants who saw no avatar. Participants who viewed avatars positioned in front of their own position made distance judgments with similar accuracy to the participants who viewed the equivalent avatar positioned at their own location.

A different approach to verify the validity of VR-based architectural reviews is to compare user's experience with a virtual model and its real counterpart. Westerdahl et al. [WSW*06] studied how employees experienced the VR model of a yet-to-be-built office building with the completed building. They found that the VR model gave a fairly accurate representation of the real building. Woksepp et al. [WO08] also studied the credibility and applicability of VR models in design and construction, in the context of an industrial plant. VR models were found to improve the review work, which was much easier and minimized the risk of misinterpretation. The design teams were able to explore different alternatives by predicting, understanding and evaluating the impact on the project as a whole.

Kuliga et al. [KTDH15] compared users' *experiences* in real and virtual environments, in the context of a conference center. They analyzed many experience-related items and found very few experiential differences between the real and the virtual environment. These differences were related to atmospherics (warmth, attractiveness and invitingness, absence of people), detailing (e.g., in terms of missing furniture) and perception of distances/sizes (VE walls/stairs/hallways felt too narrow).

Collaborative architectural design In a collaborative architectural design process, all stakeholders (users, architects, project leader, facility managers, interior designer and others) are engaged together in specific design phases [FW00]. Since collaboration improves coordination and communication within the project team and facilitates interaction with clients and end-users, several works deal with collaborative systems for VR-based architectural design [FW00, RI11, SBS15]. Frost and Warren [FW00] found that collaborative VR helped founding a common ground for the participants; untrained participants were able to understand things they would not have with traditional presentation tools (actual volume of spaces, sight lines, heights of furniture, overlapping elements...). Recently there has been an increasing interest in studying human movement when HMD users are sharing both physical and real space. Podkosova et al. studied collision avoidance preferences [PK18], and Rios et al. studied their locomotor behavior and communication strategies while performing a task that requires interaction and collaboration [RPP18].

Navigation Although VR systems allow for intuitive viewpoint control through head-tracking, natural navigation is limited to physical obstacles in the real world. Redirected walking techniques [RKW01, BSH09, SBS*12] have been proposed to allow users to explore a large virtual architectural model while remaining in a limited physical workspace. The most basic approach involves scaled translational movements and reorientation techniques to imperceptibly rotate the displayed scene around the user's position. Virtual portals [BSH09] have been proposed both for teleportation and as doorways between alternative design proposals.

There is still a large amount of ongoing research studying the impact of different navigation techniques towards reducing motion sickness [BBH*17]. Free walking is a very effective method to avoid motion sickness, but it limits the virtual displacement to the available physical space. Teleportation has also been proven to avoid motion sickness [BRKD16].

3. Distinctive aspects of the Temple

In this section we describe the most important distinguishing features of the Sagrada Família, and their impact on the VR system for reviewing and comparing alternative designs.

Challenging architectural project The building was planned from the outset to be a cathedral-sized building; the completion of the towers will presumably make Sagrada Família the tallest church building in the world. Gaudí's interest on artistic representations of nature – he said he wanted the church's interior to be "like a forest" – makes Sagrada Família a challenging architectural project in many aspects. His interest in using organic shapes that are curved instead of flat results in hyperboloid structures, helicoidal columns and curved stairways. These complex curved structures make conventional 3D CAD tools less predictive about the user experience in terms of space perception, and thus can largely benefit from immersive visual simulations.

Extremely long construction period The Sagrada Família's construction started in 1882 and is expected to be finished during next decade. During this time span, there have been significant changes in construction technologies and materials, that must coexist in harmony.

Following Gaudí Project At the time of Gaudí death in 1926, less than a quarter of the project was completed. A large part of the drawings, plans and plaster models were lost, and the documents that could be reconstructed mostly provide overall shape descriptions but lack aspects of detail design, including materials and ornaments. Today, some of the project's greatest challenges remain, including the construction of six towers requiring about 13,000 m^3 of stones. Altogether, this pushes architects towards devising multiple alternative designs for the remaining parts to find those solutions that better conform with the already built parts of the temple.

Large design team Due to the complexity and scale of the project, the different chief architects have been overseeing a team of about 16 architects. Several sculptors also play a key role on facade decoration. On such a large team, effective communication of design ideas and collaborative work is essential.

Major tourist attraction The Church is a major tourist attraction - it drew 4.5M visitors/year in 2017. This means new works must always account for the *visitor's experience* to preserve the tourism appeal of the Church.

4. Requirement Analysis

The overall goal of the VR project was to develop an automatic framework to export models from 3D CAD software into a VR application (Unity3D) for immersive visualization and comparison of alternative designs. The idea is that architects will continue using the 3D CAD tools they are famíliar with (in this case, Rhinoceros), to easily design shapes using NURBS curves and surfaces, and assign them material attributes such as stone type, color, and type of finishing, which might vary between alternative designs. At any moment where a decision must be taken, architects use our framework to export one or more alternative designs, and explore them immersively in Unity3D using a VR headset. Architects thus continue to focus on the design, without the need to have any rendering or geometry processing knowledge. When this project started, architects were already familiarized with the basic use of Unity, meaning loading models and viewing them in the HMD. Therefore this project needed to simply respect this workflow, and develop new functionalities providing interfaces similar to those in Unity.

Major application requirements we identified are listed below:

Preserve existing 3D CAD tools and design workflows The framework should allow architects to use the 3D CAD tools they have been using for years, and have minimal impact on their own design workflows. This requirement has important implications e.g. because some key material attributes might be lost in the export phase.

Fast, minimal effort conversion Considering the size of the architect teams, and the fact the tool will be used to support both global and local decisions, architects expect an easy use of the system. This means that the end-to-end process (from a given CAD model to its immersive inspection) should be fast (within a few minutes) and require minimal user assistance.

Automatic geometry preprocessing CAD conversion tools often produce models that result in visible artifacts when inspected with other tools. These artifacts could be largely distracting during design review sessions, and should be corrected automatically at export time. In our case, major artifacts were related with inconsistent per-triangle or per-vertex normal vectors (causing incorrect backface culling and wrong shading), co-planar triangles (causing flickering effects due to z-fighting), and excessive number of unnecessary triangles (causing performance drops during visualization with the VR headset).

The six central towers are being erected with tensioned-stone panels. Although this avoids a reinforced-concrete structure to support the panels, it implies that in the final phases of the design, the CAD model should represent these panels (about 800) *stone by stone* (about 21,000 stone blocks), with all details (including e.g. the holes for the steel rods used to tension the stone blocks). At building time, stones will be joined with mortar, which is obviously not represented in the CAD model. Although the lack of mortar has little effect in the CAD drawings, it has a devastating effect in terms of prediction of the visitor experience in a VR environment. Therefore the tool should automatically analyze stone blocks and fill space between neighboring stone blocks with polygons representing the mortar. Furthermore, the tool should identify hidden polygons (e.g. holes for the steel rods) and remove them from the VR model.

Figure 2: *Examples of different stone finishes.*

Procedural assignment of appearance details Architects assign each geometry part a series of attributes specifying its material type (e.g. stone, glass, ceramics, or metal). Some of these materials might also include additional information (on a per-face basis), such as the type of rock being used, or the finishing type applied to each side of a block. Figure 2 compares three different finishes for the same rock (smoothed, wrinkled and dotted).

The Montjuic stones that were traditionally used to build the Temple are no longer available, and stones from quarries around the world (including United Kingdom, France and India) must be combined and pixelated to match the color and appearance of the original blocks.

The framework must be capable of importing and showing these appearance details in the VR system. Furthermore, since per-face assignments of these attributes can be a long and tedious task, architects might want to leave out this information, and use the tool to generate automatic assignments of material attributes to stone faces, according to varying rules. These rules currently take the form of a list of material descriptions (in terms of the rock inherent attributes and finishing treatments) and desired percentage of stones that would be randomly assigned one of the prescribed materials. This would allow architects to discuss and compare multiple embodiments of a given building part with varying material assignments. The procedural material assignment should be available also within the VR application. As decision on materials of some parts are taken, the associated attributes can be fixed in the CAD model, to allow for iterative material refinement.

Surrounding environment New building parts must be in harmony with already built ones. This obviously requires inspecting the alternative designs in the context of a faithful model of the environment. Since the environment also includes neighboring buildings and cityscape, for which no 3D models are available, we decided to use spherical images taken at different heights (from the construction crane). Figure 3 shows an image taken at a height of 100m in the Jesus Christ tower that is currently being raised. The image provides a realistic 360° view of the surroundings of the building to helps the architects to visualize the temple with context.

Viewpoint control Architects should be able to define predefined viewpoints both from with the CAD tool and the VR application.

Figure 3: *Spherical image used to represent the environment from the tallest tower.*

The VR application should provide an intuitive way to navigate through the model (see next section) and to load/save viewpoints.

Collaborative review sessions The VR application should allow multiple architects to perform review sessions simultaneously and to collaborate both locally and remotely (see Section 5.3).

5. Interface design

5.1. Importing tool

In the early phases of the project, architects just wanted to be able to export CAD models (Rhinoceros toolset) and load these into a Unity-based application that supported Oculus Rift and HTC Vive VR headsets. However, it turned out that some preprocessing tasks concerning lighting and materials could be better accomplished within the Unity editor rather than manually in the CAD system.

These features are being implemented as C# scripts for the Unity3D Editor. The scripts handle both the import of the CAD model, its customization (described next), and the addition of the packages required for building a fully-featured VR inspection tool. The scripts are executed using a GUI that avoids requiring scripting/Unity knowledge.

When a model is imported within Unity, our software automatically assigns the right materials and finishing type to each face of each stone. The interface allows the architects to create a database of tones of color for a type of rock. The software recognizes the rock type and randomly assigns one of the tones from the data base. This gives the architects the possibility of choosing rock type for each block, but not having to specify the tone. Tones are assigned randomly just like it happens in reality when they are being extracted from the mountains. With the new interface the architects can also modify both the rock type and the finishing directly in Unity. The new models can be saved for later used.

The architects can easily compare models using a new loading interface developed in Unity. Architects can decide which models they want to study, and locate them in a specific folder. Then using Unity they will be able to load as many models from that folder as needed to visualize them simultaneously while wearing the HMD.

Figure 4: *Architect observing the inside of a tower using the HMD. On the TV we can see what the architect is looking at so the other architects in the room can discuss ideas.*

5.2. Virtual Reality application

Several navigation methods were implemented for this project: walking, flying and teletransport. The first two modes allow the architect to save any viewpoint in a list of favourite viewpoints that are used for the thirst navigation mode. Walking allows the architect to hold the VIVE controller in his hand, and move in a specific direction by pointing, and advancing by pressing a button. At all times the viwepoint height is computed by tracing a ray towards the floor and calculating the distance to the first collision. This guarantees that even if the architect walks down a ramp or a set of stairs, his viewpoint will always be consistent with his height. During walking navigation, the architect can toggle on and off the collision detection against walls. Therefore when collision detection is on, we have a realistic walking along the temple, whereas when it is off, we give the freedom of traversing walls (with the disadvantage of seeing back faces when traversing walls).

Flying is the least restrictive mode of navigation. The architect can point in any direction, and there is no test for height against the floor and no collision detection. This mode is not the most realistic one, but it is very convenient to quickly explore any angle of the building, and it is also very useful to save favourite viewpoints.

Finally the teletransport mode simply allows the user to change from one favourite viewpoint to the next one in the list. After each teletransportation, the architect has the freedom to look around or physically walk within the limits of the VIVE chaperone (approximately $4m$x$4m$). In this mode the architects can also reset their distance to the floor by pressing a button on the VIVE controller. This means that as they change from one viewpoint to another they can adjust the height of the viewpoint over the floor to match the exact architects' height.

5.3. Collaborative VR

Architects work individually designing different elements of the temple. However those design ideas need to be shared with other

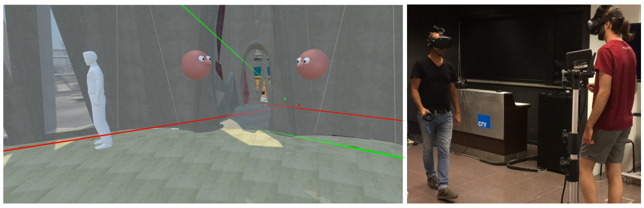

Figure 5: *On the right 2 users sharing the physical space while observing the temple with HMDs. On the left a third person view of the scene.*

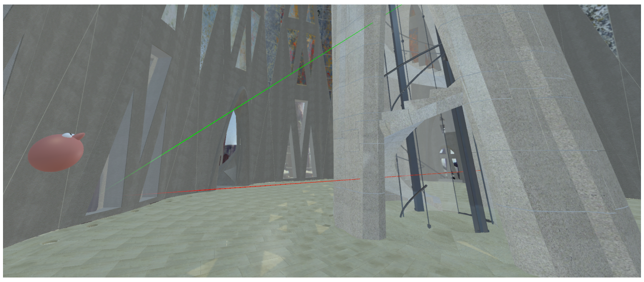

Figure 6: *View of the other user's head and pointing direction during the collaborative VR setup.*

architects for discussion, and latter on presented to the lead architect and the management team. In the first VR sessions, collaboration was done by having one user wearing the HMD and others observing the visualization on a TV. This allowed for discussion, but only one architect could be immersed in the virtual temple (see Figure 4). The main limitation of this workflow is that the audience participates as a passive viewer, with the view point set by the person wearing the HMD, and cannot perform direct interaction (e.g. cannot point at things). This leads to a rather frustrating collaborative experience, where the passive viewers have to provide verbal instructions to indicate where they want to look at, and/or to refer to elements in the environment. Similarly the user wearing the HMD gets frustrated by turning around the head and pointing device following ambiguous instructions.

During this phase of the project, we have explored different alternatives for a successful collaboration in immersive VR. The main interest of the architects was to be able to have two people inspecting the environment at the same time, to discuss design ideas. In order to do so, several things are needed. The first one is to have a knowledge of where the other user is standing, where she is looking at and also where exactly is she pointing.

During this collaborative VR, users share both physical space and virtual space, as shown in Figure 5. We considered having the physical space being different (collocated physical spaces without chance of collision between them), but given that the architects needed to talk during the experiment, sharing also physical space made the interaction more natural.

To have information about the other user, a cartoonish floating head is rendered matching the user's head tracked position and orientation (see Figure 6). This allows the other user, not only to get an idea of what the other user is looking at, but also avoid collisions between the architects. The VIVE controller continuously renders a colored ray in the direction that the controller is pointing. This works as a virtual laser pointer, and it allows both users to point at things far away from their reach to give information to the other user.

Being in the same virtual space, when the chaperone approximately matches the virtual space, makes collaboration very simple. Both users can walk within the chaperone area, look around, see where the other user is located, and share information by talking and pointing with the virtual laser. The biggest challenge comes when it is necessary to move to other parts of the building that are far away.

In order to make navigation easier, we decided to create a virtual room and only one user was in control of changing the virtual room location. This means that the second user can not navigate with the VIVE controller. The main user is thus able to move the virtual room, by either pointing with the virtual laser and pressing a button, or else using the teletransport navigation mode explained in section 5.2. In order to avoid dizziness or disorientation problems, the virtual room transitions are visually represented by a fade out/fade in rendering.

6. Challenges

Lossy export The generation of models in Rhinoceros, allows to create hierarchies of layers with additional information for each mesh or face of the model. When the architects are designing the different parts of the temple, they use these layers to classify the different parts of the geometry with information such as, material, type of rock or finishing . However, when this model is exported to be loaded into Unity, all the hierarchical information of the layers is lost, as a similar structure does not exist in any of the exporting formats. As a consequence, we had to write our own export tool to extract and save this information. After selecting the geometry to export, our exporter performs an explode of the geometry, also adding an additional layer to the resulting geometry that is named with the original name followed by the specific part name in the previous layer (the name initially assigned to each part of the geometry). Now the obj file exported will contain all concatenated name tags, so that it can be parsed by our dedicated Unity importer.

By having a specification of names for the different types of part models, the dedicated Unity importer is able to parse the final names assigned to each object (which are the result of concatenating layers of the hierarchical Rhinoceros information). As a consequence, our system automatically knows whether an object needs to be rendered as metal, glass, or stone. Furthermore, the tags parsed for each mesh object also contain the code corresponding to the finishing assigned to each stone (this is necessary since specification codes define rock types, but not the specific tone for each block of stone). Our framework uses such codes to choose the right normal map that needs to be assigned for each face.

Finally, with the interface described in section 5.1 the architects can create a database of stone tones. Then when the parser recognizes a stone identifier in the name of the mesh, it automatically selects randomly a tone from the given data base and assigns it to the mesh representing the model. Figure 8 shows the result of loading a tower with different tones of the same rock for each stone, and Figure 9 shows a close up of stones with different finishes depending on the normal map chosen.

Mortar filling Once the architects have modelled one by one the blocks, and assigned materials and finishing tones, it is necessary to fill the gaps between blocks to simulate the mortar. This is not a task to be done manually by the architects, as it would be very time consuming. But without this mortar simulation the model would not be ready for virtual reality visualization, since the gaps are visible and allow light to go through them when it should not. An automatic gap filling algorithm was thus required.

In order to create such mortar filling, the geometry must be processed in an ordered way, to determine how to create rectangles that can fit small gaps without intersecting (to avoid z-fighting problems) and without leaving remaining holes. Given the complexity of Gaudí's designs, the building blocks are not simple rectangles as in most buildings. Many blocks may have concave regions, triangular shapes, or stones with outside faces not being co-planar. Therefore the algorithm must to be robust against all those complex shapes.

Our gap filling algorithm works by sequentially processing all wall blocks and by identifying neighbour blocks. For a certain block B, the algorithm starts by extracting its visible mesh VB (the set of triangles that will be visible during the VR navigation), detecting all neighbour blocks (those blocks B_n with visible meshes VB_n being closer than a certain threshold to VB), and creating quadrilateral strips of mortar in all void gaps among VB and VB_n. Once filled, individual gaps defined by pairs of blocks (B, B_n) are flagged as non-void to avoid further processing. We use a standard sewing propagation algorithm along individual gaps which also fills all ending T and X-shaped regions.

Figure 7 shows a comparison of the building with and without the mortar filling simulation. In the case without filling it is easy to observe the light from the other side or the color of the default material assigned to non visible faces (note that this gaps are largely noticeable during a immersive VR experience). Our framework allows the user to choose the mortar color.

Figure 7: *On the top, an example of the temple with gaps between stones. On the bottom the same image with the mortar filling simulation.*

7. Discussion and future work

Prototype versions of the VR tool are been used by architects in the Sagrada Família for inspecting, evaluating and comparing alternative options since 2017. VR review sessions so far have focused on parts of the Jesus Christ spire that is currently being raised.

Here we summarize the lessons learned after one year of use of a VR tool:

Seamless integration with existing CAD tools A key aspect for the true usefulness of the project has been the integration of the VR review sessions with the architects' current workflow. A fast, simple procedure to port and prepare 3D CAD models for VR inspection, together with the setup of the VR equipment at the architect's studio space has turned out to be critical for successful use of the VR system.

The architects consider that the limited time needed to export geometry from Rhinoceros into Unity, offers them high performance to make fast tests of an initial design.

They have recently started to test the block exploding system, which is a bit more complex but easy to use. The explode system splits the block mesh into sub-meshes, so that the architects can make specific changes to block sides. It offers a menu which allows the architects to randomly assign material to each surface, and then a predefined normal map is automatically assigned. This has further improved the architects' feeling of realism.

Space Perception Since the early tests of the VR headsets, architects at Sagrada Família have been specially concerned about the accuracy of the VR visual simulation in terms of prediction of the visitors' experience. A major issue is the perception of spaces and distances as close as possible to the real ones. This is particularly challenging in the Sagrada Família case. Gaudí's preference for curved shapes over traditional architectural designs results in images hardly exhibiting vanishing points and linear perspective depth cues (Figure 1), which play a key role in depth perception within architectural spaces. We have observed head tracking (providing view-motion parallax depth cues) to greatly improve depth percep-

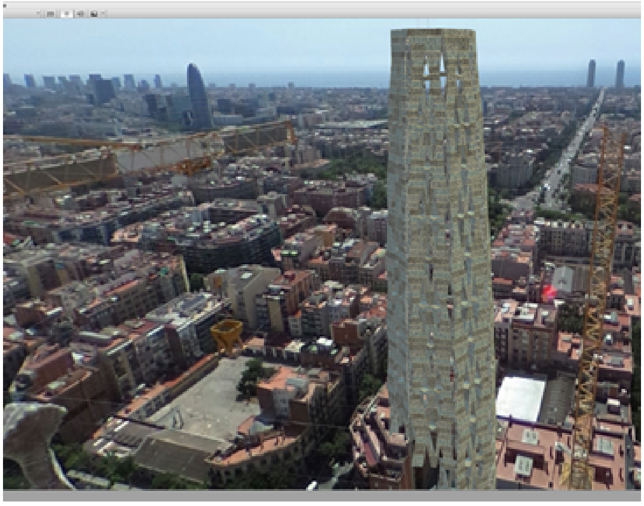

Figure 8: *Part of the Jesus Christ tower with the spherical image of Barcelona. The tower shows the result of applying the same rock type to all the blocks but with random assignment of tones.*

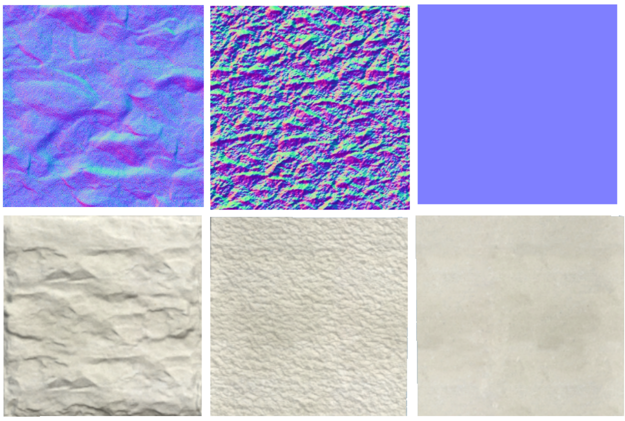

Figure 9: *Examples of normal maps applied over the same rock type to achieve a variety of appearances.*

tion. Other techniques we are currently using to reinforce depth perception include adding visitors' avatars to provide a Famíliar-object size reference, and room-sized interaction (promoting physical walking and minimizing motion sickness, which so far has not been experienced), which motivated the move from Oculus Rift to HTC VIVE headsets. Architects consider that HTC VIVE provided an improved visualization, sharper images and an overall enhanced immerssive experience. They also commented on the new navigation modes, that they find more practical and intuitive, which also motivated the move to collaborative work.

Need for collaboration Since many decisions in the Sagrada Família are not taken individually but by a team of architects, collaborative review sessions and effective communication among designers has been a priority since the outset of the project. On the other hand, we have observed that collaboration tools do not need to be highly sophisticated; viewpoint/navigation sharing and head position awareness has been found to be enough at this stage of the project.

As future developments, the most immediate priorities relate with handling the increasing model complexity due to larger detailed contexts and scanned sculptures being added (through model simplification, level-of-detail, and multiresolution techniques [PD16, CCD*11]), and improving lighting simulation, specially sunshine passing through stained glass windows.

Architects also suggested to further reduce the computational time for the export tool, assignation of materials and visualization with the HMD. In this last case, they suggested that models that have already been consolidated may be blocked to speed up all the computation required for visualization. The mortar filling algorithm will have to be adjusted to also fill the gaps between consolidated models. To do so, we would like to evaluate a functional approach that could handle each stone as a semantic entity. At midterm, we wish to allow design reviews to be explored too using an augmented reality system.

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References

[AEI03] Anderson L., Esser J., Interrante V.: A virtual environment for conceptual design in architecture. In *Proceedings of the workshop on Virtual environments 2003* (2003), ACM, pp. 57–63. 2

[BBH*17] Bergmann T., Balzer M., Hopp T., van de Kamp T., Kopmann A., Jerome N. T., Zapf M.: Inspiration from vr gaming technology: Deep immersion and realistic interaction for scientific visualization. In *VISIGRAPP (3: IVAPP)* (2017), pp. 330–334. 3

[BBWB10] Bullinger H.-J., Bauer W., Wenzel G., Blach R.: Towards user centred design (ucd) in architecture based on immersive virtual environments. *Computers in Industry 61*, 4 (2010), 372–379. 2

[BPF*18] Bekele M. K., Pierdicca R., Frontoni E., Malinverni E. S., Gain J.: A survey of augmented, virtual, and mixed reality for cultural heritage. *J. Comput. Cult. Herit. 11*, 2 (Mar. 2018), 7:1–7:36. 2

[BRKD16] Bozgeyikli E., Raij A., Katkoori S., Dubey R.: Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play* (New York, NY, USA, 2016), CHI PLAY '16, ACM, pp. 205–216. 3

[BSH09] Bruder G., Steinicke F., Hinrichs K. H.: Arch-explore: A natural user interface for immersive architectural walkthroughs. In *3D User Interfaces, 2009. 3DUI 2009. IEEE Symposium on* (2009), IEEE, pp. 75–82. 3

[CCD*11] Callieri M., Chica A., Dellepiane M., Besora I., Corsini M., Moyés J., Ranzuglia G., Scopigno R., Brunet P.: Multiscale acquisition and presentation of very large artifacts: The case of portalada. *J. Comput. Cult. Herit. 3*, 4 (Apr. 2011), 14:1–14:20. 8

[CW94] Campbell D. A., Wells M.: A critique of virtual reality in the architectural design process. *University of Washington HITL Technical Report R-94 3* (1994). 2

[DR99] Donath D., Regenbrecht H.: Using immersive virtual reality systems for spatial design in architecture. In *AVOCAAD'99 Conference Proceedings* (1999), pp. 307–318. 2

[FW00] FROST P., WARREN P.: Virtual reality used in a collaborative architectural design process. In *Information Visualization, 2000. Proceedings. IEEE International Conference on* (2000), IEEE, pp. 568–573. 3

[IMTP17] IOANNIDES M., MAGNENAT-THALMANN N., PAPAGIANNAKIS G.: *Mixed Reality and Gamification for Cultural Heritage*. Springer, 2017. 2

[IRA06] INTERRANTE V., RIES B., ANDERSON L.: Distance perception in immersive virtual environments, revisited. In *Virtual Reality Conference, 2006* (2006), IEEE, pp. 3–10. 2

[IRL*08] INTERRANTE V., RIES B., LINDQUIST J., KAEDING M., ANDERSON L.: Elucidating factors that can facilitate veridical spatial perception in immersive virtual environments. *Presence: Teleoperators and Virtual Environments 17*, 2 (2008), 176–198. 2

[KTDH15] KULIGA S. F., THRASH T., DALTON R. C., HOELSCHER C.: Virtual reality as an empirical research toolâĂŤexploring user experience in a real building and a corresponding virtual model. *Computers, Environment and Urban Systems 54* (2015), 363–375. 2, 3

[MCB*14] MORTARA M., CATALANO C. E., BELLOTTI F., FIUCCI G., HOURY-PANCHETTI M., PETRIDIS P.: Learning cultural heritage by serious games. *Journal of Cultural Heritage 15*, 3 (2014), 318–325. 2

[MCRTB10] MOHLER B. J., CREEM-REGEHR S. H., THOMPSON W. B., BÜLTHOFF H. H.: The effect of viewing a self-avatar on distance judgments in an hmd-based virtual environment. *Presence: Teleoperators and Virtual Environments 19*, 3 (2010), 230–242. 3

[MTP05] MAGNENAT-THALMANN N., PAPAGIANNAKIS G.: Virtual worlds and augmented reality in cultural heritage applications. *Recording, modeling and visualization of cultural heritage* (2005), 419–430. 2

[PD16] PONCHIO F., DELLEPIANE M.: Multiresolution and fast decompression for optimal web-based rendering. *Graphical Models 88* (2016), 1–11. 8

[PK18] PODKOSOVA I., KAUFMANN H.: Mutual collision avoidance during walking in real and collaborative virtual environments. In *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games* (New York, NY, USA, 2018), I3D '18, ACM, pp. 9:1–9:9. 3

[RI11] RAHIMIAN F. P., IBRAHIM R.: Impacts of vr 3d sketching on novice designers' spatial cognition in collaborative conceptual architectural design. *Design Studies 32*, 3 (2011), 255–291. 3

[RKW01] RAZZAQUE S., KOHN Z., WHITTON M. C.: Redirected walking. In *Proceedings of EUROGRAPHICS* (2001), vol. 9, Citeseer, pp. 105–106. 3

[RPP18] RÍOS A., PALOMAR M., PELECHANO N.: Users' locomotor behavior in collaborative virtual reality. In *Proceedings of ACM SIGGRAPH Conference on Motion Interaction and Games* (New York, NY, USA, 2018), MIG '18, ACM. 3

[RVH13] RENNER R. S., VELICHKOVSKY B. M., HELMERT J. R.: The perception of egocentric distances in virtual environments - a review. *ACM Comput. Surv. 46*, 2 (Dec. 2013), 23:1–23:40. 2

[SBH*09] STEINICKE F., BRUDER G., HINRICHS K., LAPPE M., RIES B., INTERRANTE V.: Transitional environments enhance distance perception in immersive virtual reality systems. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization* (2009), ACM, pp. 19–26. 2

[SBS*12] SUMA E. A., BRUDER G., STEINICKE F., KRUM D. M., BOLAS M.: A taxonomy for deploying redirection techniques in immersive virtual environments. In *Virtual Reality Short Papers and Posters (VRW), 2012 IEEE* (2012), IEEE, pp. 43–46. 3

[SBS15] SCHMIDT S., BRUDER G., STEINICKE F.: A layer-based 3d virtual environment for architectural collaboration. In *Proceedings of the EuroVR Conference* (2015). 3

[SWKM95] SCHMITT G., WENZ F., KURMANN D., MARK E. V. D.: Toward virtual reality in architecture: concepts and scenarios from the architectural space laboratory. *Presence: Teleoperators & Virtual Environments 4*, 3 (1995), 267–285. 2

[Why03] WHYTE J.: Industrial applications of virtual reality in architecture and construction. *Journal of Information Technology in Construction (ITcon) 8*, 4 (2003), 43–50. 2

[WO08] WOKSEPP S., OLOFSSON T.: Credibility and applicability of virtual reality models in design and construction. *Advanced Engineering Informatics 22*, 4 (2008), 520–528. 3

[WSW*06] WESTERDAHL B., SUNESON K., WERNEMYR C., ROUPÉ M., JOHANSSON M., ALLWOOD C. M.: Users' evaluation of a virtual reality architectural model compared with the experience of the completed building. *Automation in construction 15*, 2 (2006), 150–165. 3