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Short Paper

Seismic Simulation on Virtual Reality

Josep Lluis Fita, Gonzalo Besuievsky and Gustavo Patow

ViRVIG, University of Girona, Spain

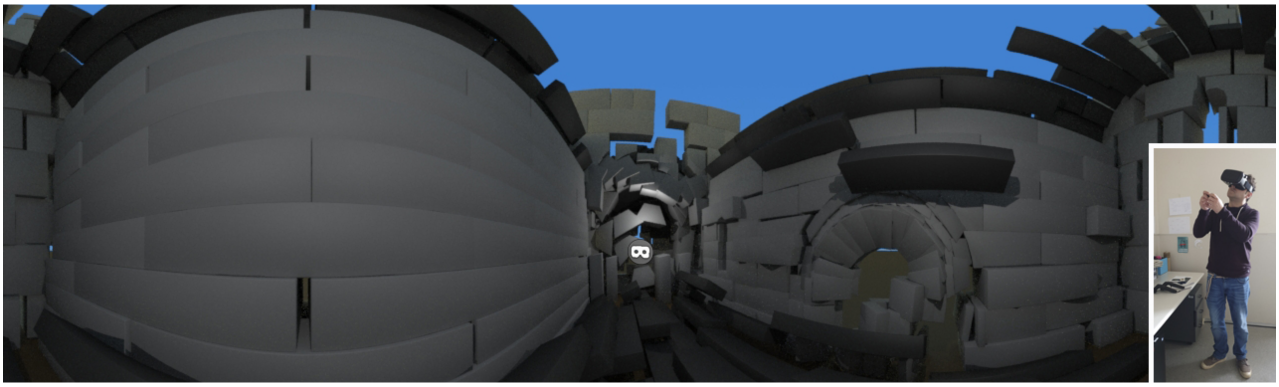

Figure 1: *A spherical view of the* Sant Bartomeu de Pincaro *church recreation under seismic movements used in our virtual reality application. Inset: a user testing it with the headset and controller.*

Abstract

Virtual Reality has been used in Cultural Heritage for providing immersive experiences of recreated and static environments to the final user. However, there is a lack of virtual reality applications for recreating natural phenomena like earthquakes in combination with structural simulations over ancient masonry buildings. In this paper, we describe a solution affordable for all kind of users and designed for running on low-cost devices, where users can have an immersive experience in a virtual environment, where the structural and seismic simulation affects a historical building.

CCS Concepts

• ***Computing methodologies*** → ***Physical simulation;*** • ***Applied computing*** → *Virtual Reality;*

1. Introduction

The research and improvement on new techniques in Computer Graphics have benefited fields like Cultural Heritage, where the efforts have been focused on the digital preservation of artefacts and architectonic structures through the development of methodologies for recreating ancient buildings as simple 3D objects. However, the most part of the efforts in this area have not been focused on the simulation of natural phenomena, such as earthquakes and their effects on 3D modelled historical buildings. Additionally, the use of Virtual Reality in Cultural Heritage has been focused on the recreation of ancient environments or past events for running on powerful and expensive hardware.

In Cultural Heritage, the design of applications for Virtual Reality that combine building modelling, structural and seismic simulation, and that at the same time is accessible for all kinds of users, is practically testimonial. On the other hand, low-cost devices such as smart-phones are ubiquitous nowadays, but the hardware of those devices has, in general, low power capabilities. This leads to a deadlock situation where low-cost devices are ubiquitous, but they are incapable of running the high-complexity applications required for simulation of both structural analysis and seismic movement recreation, with the fidelity requirements of Virtual Reality interactions.

In this paper, we have focused on designing a solution for low-cost devices based on exporting our simulations for the recreation effects of seismic movements on masonry buildings into the 360° Virtual Reality video format. Our application is completely based on off-the-shelf tools and is designed to be visualized on a low-cost smart-phone with headsets, providing an immersive but affordable experience for Cultural Heritage users.

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2. Previous Work

One common approach for the recreation of historical buildings is the use of procedural modelling techniques, such as the one presented by Muller et al. [MWH*06] based on shape grammars. Later, other authors have created extensions using shape grammars such as a visual language by Patow [Pat12], extended expressions by Krecklau and Kobbelt [KK12], or the inclusion of primitives by Schwarz and Müller [SM15]. On the other hand, new techniques have been developed using different approaches. Saldana and Johanson [SJ13] presented a technique that allows the reconstruction of buildings from GIS data. Capellini and co-workers [CSS*13] based on modelling of masonry buildings through photogrammetric data. However, these techniques have been designed only for modelling, not taking into account other aspects of the construction process. One of the technique that combines the shape of a building with structural simulation was presented by Whiting and coauthors [WOD09], where they recreated an historical church and applied structural analysis for studying its stability. Later, Whiting et al. [WSW*12], studied the structural problem with restrictions introduced by the users in the final model of a building. Panozzo and co-authors [PBSH13] presented an approach where a 3D masonry structure is created minimizing the differences from a user-provided input surface. Later, Deuss et al. [DPW*14] extended this work for all kind of masonry shapes. Furthermore, the combination of the structural simulation and earthquake simulation has led to some interesting works, mainly in Civil Engineering, such as the ones by Altunisik and co-workers [AAG*16] or Castori and colleagues [CBM*17]. Ramos and Lourenco [RL04] developed a methodology that allows rebuilding the historical centre of Lisbon.

Virtual Reality is used in Cultural Heritage for giving an immersive experience to users. The state-of-the-art presents some works such as the one by Gaugne and co-workers [GSN*18] presented a work where some artefacts are shown as a user interface. An immersive experience given by 360° VR was presented by Selmanovic et al. [SRH*18]. Andujar and co-authors [ABB*18] introduced a VR-based project that combines CAD tools to model with VR tools to review new structures for the Sagrada Family Cathedral. For more information, please refer to the review by Mortara and coworkers [MECB*14] or the survey presented by Bekele and colleagues [BPF*18].

3. Seismology

An Earthquake is a movement that occurs at a point, known as focus, between the tectonic plates inside the crust of the Earth. The liberated energy travels inside of the Earth through the medium in two ways: *Longitudinal* waves or *P-Waves*, which move back and forth by compression; and *transverse* waves or *S-Waves*, which move by vibration in solid particles. When these two movements, known as body waves, reach a point of the Earth surface, known as earthquake epicenter, they create surface waves that propagate along the Earth's surface. These waves have lower velocity with respect to body waves and their amplitude becomes lower with the increment of the medium depth. These waves are the main responsible for the environment destruction. A deeper description of earthquakes can be found on the mathematical development of Lowrie [Low07] and Rawlinson [Raw08].

Figure 2: *Our pipeline: A simulation is processed, and the resulting animation is rendered trough a camera tailored for Virtual Reality. The 360° video obtained is exported to the Virtual Reality application that displays it on a headset.*

Rayleigh waves: Their motion is a combination of the two types of body waves. The mathematical description of these waves is given by the position equation for the x and z-axis at the free surface, assuming the wave travels in the y-axis.

$$\theta_x(x,t) = a\left(\frac{\omega^2}{2k\beta^2}\right)\cos\left(kx-\omega t\right), \tag{1}$$

$$\theta_z(x,t) = a\left(\frac{2k\kappa_\alpha}{k^2+\kappa_\beta^2}\right)\left(\frac{\omega^2}{2k\beta^2}\right)\sin\left(kx-\omega t\right), \tag{2}$$

where $\kappa_\alpha^2 = k^2-(\omega/\alpha)^2$ and $\kappa_\beta^2 = k^2-(\omega/\beta)^2$. Equations 1 and 2 show the main features such as the angular frequency ω and wave-number k of the *Rayleigh waves*, and describe the motion of these as retrograde and elliptical parallel to the direction of propagation.

Love waves: The motion of these waves comes from the transverse body waves. These are faster than *Rayleigh* waves and travel along the Earth surface in groups, described by the so called *carrier* and *envelope* waves. The mathematical description is given by the position equation as a sum of two harmonic waves that can be described as a product of two cosine functions.

$$\theta_y(x,t) = a2\cos(kx-\omega t)\cos(\delta kx-\delta\omega t). \tag{3}$$

Equation 3 describes the *Love* wave position at a given time, where the carrier wave has an angular frequency ω and wave-number k and the envelope wave has a lower angular frequency $\delta\omega$ and wave-number δk.

We based our simulation in the reproduction of the surface waves, both *Rayleigh* and *Love*, following the mathematical description given by Equations 1, 2 and 3. The Earthquake magnitudes have been modeled by Equation 4, which is an adaptation of the original Richter formula [Raw08] as:

$$M = \lg A + 3\lg(8\Delta t) - Q, \tag{4}$$

where A is the amplitude recorded from the seismograph, Δt is the time between the two type of body waves, Q is the regional scaling factor and M is the magnitude number of energy released by the earthquake.

4. Overview

The combination of structural and earthquake simulations is unfeasible in real-time because of the computational resources required, which precludes its usage in low-cost devices such as smartphones that usually have a low power hardware for handling the geometry and animation requirements. Our pipeline is presented at Figure 2.

The earthquake simulation tool: is based on a off-the-shelf tool and has been designed with the following elements according to a bottom-up perspective:

The surface wave simulator allows the simulation of the surface waves that take part in an earthquake, according to the Richter scale magnitude. Also, it has an interface designed for non-expert users allowing the configuration of magnitude, orientation and frequency of the waves.

The Ground is a grid with a size of $1500m \times 1500m$ controlled by the surface wave simulator with physical features such as *friction coefficient* and that reacts to the earthquake movements.

The dynamic network collects all geometry data from the modelled building and the ground for the physics engine, the *Bullet* [Lib16] solver library, which is capable of detecting and resolving collisions among the simulation objects.

An input geometry of an ancient masonry building is imported in the simulator and connected through the dynamic network, where the positions of the lowest layer of bricks at the ground are being controlled by the surface wave simulation. This is called *position process*. The building has been configured with physical features such as *density*, with a value of $2691kg/m^3$ for simulating the granite stone; the *friction coefficient* value, of 0.7; and the *glue* component, which simulates the mortar used to give some cohesion between the bricks.

When the simulation starts, the main parameters given by the user through the interface are used to calculate the *angular frequency*, the *phase velocity* and all relevant parameters required for the simulation of the surface wave motion involved in the earthquake. Then, the grid geometry is loaded. The first step is to determine if the wave-front has arrived from its epicenter, computed as a simple linear velocity calculation. If the result is positive, then Equations 1, 2 and 3 are applied. These steps are repeated for each ground point during the simulation, where the surface wave simulator sends the position data of the grid through the dynamic network, which in turn, is controlled by the physics engine that applies the changes over the masonry building.

Spherical Video: The implementation of the surface wave tool previously described allows us to obtain an earthquake simulation over an ancient stone building. However, as mentioned before, the direct results of these simulations are unfeasible to be exported to a low-cost VR device, so we exported these results as a set of 360°VR videos, as shown in Figure 2. The spherical video has been designed to be displayed inside of a spherical shell, where the system corrects any perspective-induced deformation. Spherical video rendering has been carried out through a set of specific cameras located around and inside of the main building with the aim of recording different points of view of the same simulation. Also, each camera has been configured with a specific capture angle for rendering with a realistic *ray-tracing* algorithm, using an *equirectangular* projection, mono, see Figure 1. When the set of 360°VR videos has been recorded, we load them into a virtual reality application that allows to see, in real time, the results of the simulations on a low-cost headset, as shown in Figure 2.

Virtual Reality App: We have used the *Unity 3D engine* [Uni05], with the idea of generating an immersive experience inside a scenario recreating an historical event where an earthquake took place. As we target low-cost devices appropriate for exhibitions and mass events, our implementation was designed for the *Google Daydream or Cardboard*. which only allows the user the *three-degrees-of-freedom* (3-DOF), with a fixed viewpoint position for interacting with the 3D space. The video controller of the Head Mounted Display has been configured with functions such as play and pause, video forward or rewind, and teleportation node selection.

The application 3D space has been designed for displaying the imported and pre-recorded 360°Virtual Reality videos generated with *Houdini*. The videos are controlled by C# scripts and rendered as a shaders inside of a *photo-sphere* surface using an *equirectangular* image. In its center, we have located the main camera that gives an interactive user-environment for the immersive first-person experience. This video rendering technique is a suitable solution for the proposed problem because requires less computing power than a full 3D scene rendering for reproducing real-time structural simulations, as shown in Section 5.

Immersed in this scenario, users can see interactive nodes, C_i, that are part of an undirected graph $G = (V,E)$ located on the exterior and interior of the church, where V is the set of the graph nodes C_i (we add an extra I superscript to refer to the nodes in the interior of the building C_i^I, just for clarity of presentation); and E a set of edges, each defined as a pair of nodes $< C_i, C_j >$, where the user can move from node C_i to node C_j. From this graph, locomotion has been designed for user teleportation among specific nodes distributed over the space. We have designed this kind of locomotion with the aim of reducing the motion sickness that is caused by lags in screen updates, colliding with the user brains who expect synchronized changes. We have added to our motion system a gaze-based point for helping the user interaction. When the gaze point is over a node of interest, it changes its color from white to blue.

5. Results and Future Work

We have performed a test over a set of stone structures with the aim of verifying the viability of exporting the 3D full scene into the virtual reality application.

The Memory Test: analyzes the efficiency of our 3D earthquake simulation scenario, computing the memory spent for different masonry structures. Through it, we can see that the structural and earthquake simulation in real-time is not possible because of the high computational memory involved. For this, we set the Richter magnitude with a value of 7.0 and the *wave-front direction* pointing to the North. We tested different ancient masonry structures such as a single wall without battlements, composed of 45 bricks; a house of 336 bricks; and a church recreation of *Sant Bartomeu de Pincaro* with 511 bricks. All these structures have been modelled with physical features described in the last section. The tests have been performed by testing each masonry structure for each simulation, where we have measured the number of bricks and the memory spent in each simulation. In Figure 3, we can see the results that shows the direct relation between the number of bricks

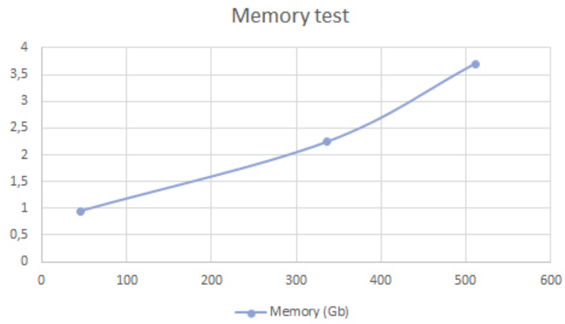

Figure 3: *The graphical results of the tests show the memory spent in each simulation increases in relation with the number of bricks tested.*

and the memory spent by the simulator to perform the computations. The memory spent by the simulation increases linearly from values of 0.94 up to 3.70 Gb. The RAM memory consumption is unfeasible for low-cost devices such as smart-phones because these devices have around 3 Gb of memory. Thus, the solution presented here is affordable to run on low cost platforms such as the above mentioned ones. On the other hand, could be of great interest for cultural heritage managers as a way of attracting new visitors to their institutions. Especially those visitors who want to experience in first person past events where an earthquake took place, (e.g., the destruction of Pompeii).

Our future work focuses on further improvements on the user interface, where we would like to present additional information about the represented building. We want to improve the earthquake simulation by adding cracks over the walls. Also, we want to improve the rendering and the performance, including a realistic appearance of granite stone. Finally, we would like to assess the practicality of our system by performing a usability study that involves cultural heritage researchers, among other users, with the aim of obtaining technical feedback about the application.

Acknowledgments

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