The "Botafumeiro" VR: Virtual Reality in the Liturgy of the Middle Ages

Abstract

Santiago de Compostela, a city in Galicia, in the northwest of Spain, has been a famous Christian pilgrimage site since the Middle Ages. One distinctive element of the liturgy of the Cathedral of Santiago de Compostela is the use of a giant censer "O Botafumeiro." It is tied to a rope that hangs from the center of the transept of the arms of the cathedral, and it is pulled through the transept of the cathedral, basically describing a pendulum movement. A team of men called "Os Tiraboleiros" pulls the supporting rope in a pumping cycle to increase the energy of the system, and therefore the angle of oscillation. This pumping process transforms the pendulum motion into a variable-length pendulum motion. We present the specific case of the virtual simulation of the liturgy of the Botafumeiro by VR techniques. The simulation allows users to play the role of the Tiraboleiros as a part of this old tradition. We present the system architecture, the design of the visualization system, a special user interface that simulates the pull of the Botafumeiro, and the experiences of its use with different users of the system.

1   Introduction

The rite of the Botafumeiro dates back to more than seven hundred years, to around the fourteenth century when it became part of the liturgy of the cathedral. (See figure 1.)

Historically, the pumping procedure has not always been the same, varying from several short pulls to a single pull during the oscillation, looking to obtain an optimum pumping protocol. It could have two main causes: first, its use started several years before the movement of the pendulum had been studied; second, the task was developed by the Tiraboleiros themselves. The Tiraboleiros work as a team, led by the chief verger of the cathedral who marks the pulling instant, calling orders where required. It is a team effort, in which the body's self-perception is not involved as in, for example,

a swing where a child would learn to pump by himself from his unconscious perceptions. The learning process involves only the chief verger who studies the evolution of the system under different protocols of pumping.

At the present time, the chief of the Tiraboleiros starts the liturgy pushing the Botafumeiro to its initial oscillation (approximately 13 deg.) with a pendulum movement though the cross of the cathedral. From that moment, the Tiraboleiros add energy cyclically to the system by increasing and decreasing the length of the rope at the highest and lowest points of oscillation, respectively. So the angle of oscillation is increased up to a maximum of approximately 80 deg. Mathematically, this dynamic movement is an example of the parametric amplification by pumping (Walker & Walker, 1977).

The first studies of the movement of the Botafumeiro, besides the description by members of the church, were undertaken by different authors who presented several mathematical models. The most significant one is the paper by R. Sanmartin (1984). It presents a detailed analysis of the movement of the Botafumeiro using energy equations. The data obtained from this analysis were corroborated by field data that certified this solution. Nevertheless, the approaches and simplifications made in this study in particular, the consideration of the process of pumping at the point marked by tradition, were not appropriate to describe the case of a Tiraboleiro with a random pull. However, the rigor of the analysis presented in the article suggest its use as the basis to obtain data such as masses, details of the rope, frictional coefficients, and so forth. From the graphical point of view, some representations have been made in several exhibitions of synthetic videos of the censer with pendulum dynamics and no type of interaction with the user.

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Figure 1. *The real Botafumeiro.*

Figure 2. *Trajectory.*

Virtual reality is a constantly evolving area of computation in which the main goal is the generation of the sensation of presence of a user in synthetic environments by the stimulation of the user's senses, in real time, by the use of immersion and interaction devices. The sensation of presence is especially important in the field of simulation and training. In these kinds of applications, the user feels immersed in the virtual environment that re-creates a special real-life situation.

We have developed a simulator of the liturgy of the Botafumeiro wherein the users act as Tiraboleiros, forming part of the tradition, at least virtually. The paper presents the phases of the development of the simulator: resolution of the equation of the movement of the Botafumeiro, discussion of the architecture of the system, development of a human-machine interface that allows the user to pull the rope like a Tiraboleiro and develop a display in which the environment can be re-created with a high degree of presence. The results of this study, in which simulation are used to facilitate evaluation of the user's attempts at optimizing the pulling process are discussed.

2   Mathematical Model: Oscillation and Pumping

To resolve the energy equations, it is necessary to analyze the trajectory of the Botafumeiro as shown in the diagram by Juan R. Sanmartin in figure 2. If we ignore the pumping process and air drag, the Botafumeiro is only a pendulum with constant energy,
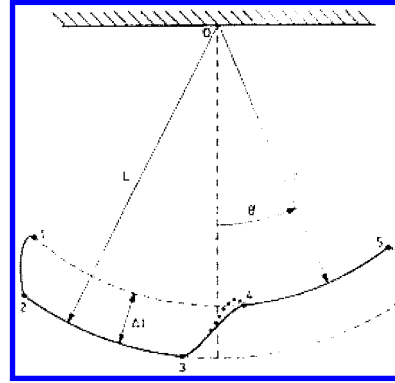
$$E = T + U = \frac{1}{2}ML^2\left(\frac{d\theta}{dt}\right)^2 + MgL\left(1 - \cos\theta\right), \quad (1)$$

where E is the energy of the system,

T the kinetic energy,

U the potential energy,

θ is the angle between the rope and the vertical plane and,

M the mass of the Botafumeiro. If we describe the pull process, we need to introduce additional variables: θ_{tiro} (angle of the pull), θ_{max} (angle for the maximum amplitude of oscillation) where the angular speed is 0, and ΔL (the length pulled), and the equations take the form of equation (2). In the tradition of θ_{tiro} are the transitions 1→2 and 3→4 in figure 2: $\theta_{tiro} = 0$ and $\theta_{tiro} = \theta_{max}$:

$$\Delta E = Mg\Delta L\left(3\cos\theta_{tiro} - 2\cos\theta_{max}\right) \qquad (2)$$

If we want to include the first-order air drag correction in this equation and express it in terms of the change of the angle of oscillation, the equation is

$$\cos\theta_{max+1} - \cos\theta_{max} = -\left(\frac{\Delta L}{L}\left(3\cos\theta_{tiro} - 2\cos\theta_{max}\right)\right.$$
$$\left. - 2\varepsilon P(\theta_n)\right)\left(1 - \cos\theta_{max}\right), \qquad (3)$$

where εP includes air drag friction and the geometric parameters of the Botafumerio and rope.

One important point of these equations is that, if the

pumping process is performed traditionally, the equations are identical to those obtained in equation (2) and the transmission of the energy to the system is maximized. The equation obtained is nonlinear; therefore, it is very difficult to resolve it empirically or analytically. It is not probable that in the Middle Ages or in the present it could be resolved without great mathematical knowledge. In this way, only the experiences of the Tiraboleiros and specifically their Chief play a basic role in the performance of the pumping. However, nowadays it can be resolved numerically, at least partially, if we know the variation of the length ΔL in time. This variation is used to recalculate the trajectory (position, speed, $\theta_{tiro} \ldots$) in every pumping cycle.

3 Architecture

The simulator system allows the "virtual Tiraboleiro" to pull the censer in the virtual environment of the Cathedral of Santiago de Compostela. It is composed of three main elements: the display (image and sound), the simulation engine, and the interface.

The display and the simulation engine work together to render the scene, sound, and images. The display is a three-screen semi-immersive large display. The scene is generated by a cluster of PCs that are coordinated by the simulator engine over a LAN. The interface is a metaphor with the real liturgical rope of the Botafumeiro; the user pulls the rope in the characteristic liturgical manner of the Tiraboleiros. This interface is managed by the simulation engine to modify the virtual Botafumeiro dynamics in the scene.

4 Display and Simulation Engine

The display must generate a realistic representation of the scene. At present, most of the systems adopt one of three possible display configurations: "traditional" VR displays (HMD and CAVE) and a third, immersive or semi-immersive large display systems using PC platforms. This last configuration is especially interesting, and a current research area in computer graphics is the use of low-cost equipment (such as PCs) in complex applications requiring high image and sound quality.

Large displays can be implemented in two ways. The first is based on developing a single large-scale projection using the native resolution of the graphical subsystem (Hereld, Judson, & Stevens, 2000; Kai Li et al., 2000). The second is based on the use of multiprojection systems in which multiple subsystems show a section of the final scene. The second option improves the resolution of the system, but it also introduces the problem of coordination of multiple elements. In this case, the architecture of the system must guarantee perfect coordination and communication between all its components. One example of this kind of architecture is NAVE (Flores et al., 2000; Hodges et al., 2000), a three-screen environment. The screens are positioned at 120 deg. to each other, producing a three-sided display area, and the user is in a seat positioned at the center of the semicircle formed by the three screens. The scene is generated by a cluster of four PCs in a server/client architecture. The image for each of the three screens is generated on a PC and is back-projected in stereo by means of polarized light; these subsystems function as graphic clients. The fourth PC functions as the server, coordinates three graphic clients, sound, and manages the different interfaces with the users.

With this philosophy of design, a large semi-immersive system was developed. The difference from the original NAVE is that the image in each of the screens is generated by two computers and back-projected in stereo by two projectors. The images from the left and right eye from independent projectors are polarized and overlaid on the screen to generate the final scene.

The use of two computers and projectors instead of one for stereo image generation has advantages and disadvantages. The advantages are associated with the increase in the frame rate and in the resolution of the system. The use of one projector for the generation of the stereo images by interleaving techniques implies the rendering of two images and the combination of both in each frame by the same computer. In the dual-projection system, these processes are handled by two independent but coordinated computers, one to generate the right image and the other the left eye image, thereby potentially increasing the frame rate by at least 50%. Another advantage is the increase in resolution. In the first case, the resolution of the projector is shared by
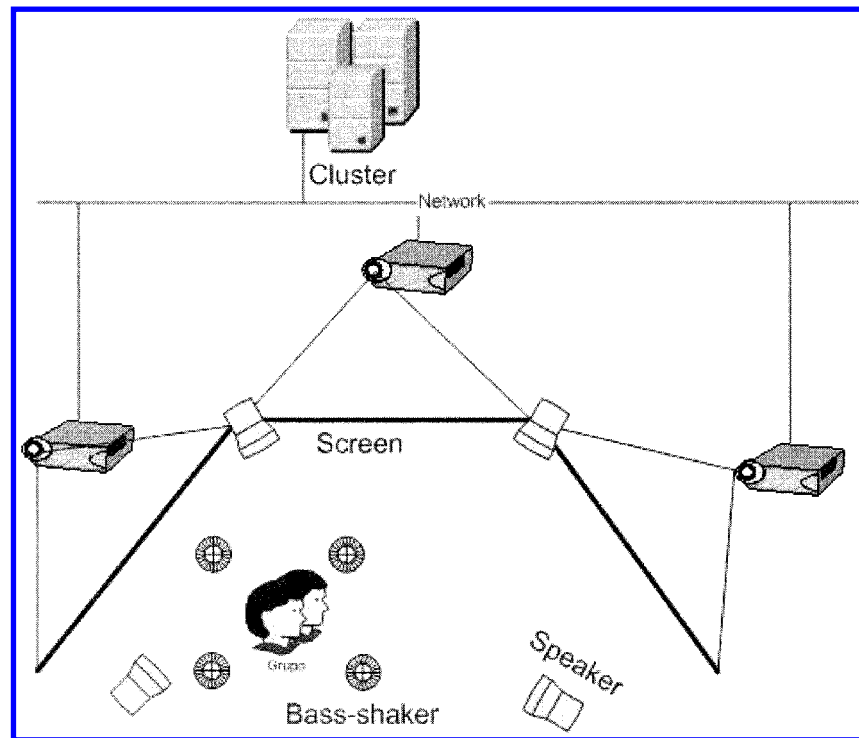
Figure 3. *Diagram of the system.*

both the left and right eye image. Using independent projectors, the image of each eye is presented at the maximum resolution of the projector. The disadvantage in the implementation of this system is the difficulty in obtaining a perfect coordination between the PCs, and the correct alignment of the projectors is more tedious. Therefore, the system has to be able to minimize the latency in data transmission and to decrease the load, processing, and reception time of messages.

The cluster structure determines the design of the simulation engine. The engine runs a copy of the application in every PC of the cluster. The copies perform different tasks depending whether they run in the server or in the graphics client. The main task of the server is to coordinate the cluster. It receives and manages the information from the interface, calculates the position of the Botafumeiro (using the mathematical model) and tracks the user in the environment, sends this information to the graphics client, and renders the directional sound. The graphical output in the server has low resolution and is only an informative display about the performance of the sys-

tem to the operator. The graphics client get the necessary information via the network and renders the high-quality graphic images using real rendering techniques, polygonal optimization, texture compression, multitexture, L.O.D., and so on.

In our case, the cluster is a set of six graphic clients and a server linked by an Ethernet 100 Mbps LAN. The display has a resolution of 3072×768 pixels per eye with passive stereographic vision over three screens with a 120 deg. of angle between them (1024×768 pixel per screen and eye). From the position of the user(s), the structure covers approximately 210 deg. Therefore, it covers the angle of view of the user adequately to produce a visual sense of presence. (see figure 3.)

The sound is a very important element of the system. The audio system is composed of four speakers, a passive subwoofer, and a pair of bass-shakers to maximize bass vibration effects. The sound system features a Sound Blaster Live and a PCI-128, the former for the directional sounds and the latter to generate the vibration and some generic sounds. The bass-shakers are installed under the floor where the users stand (figure 3).
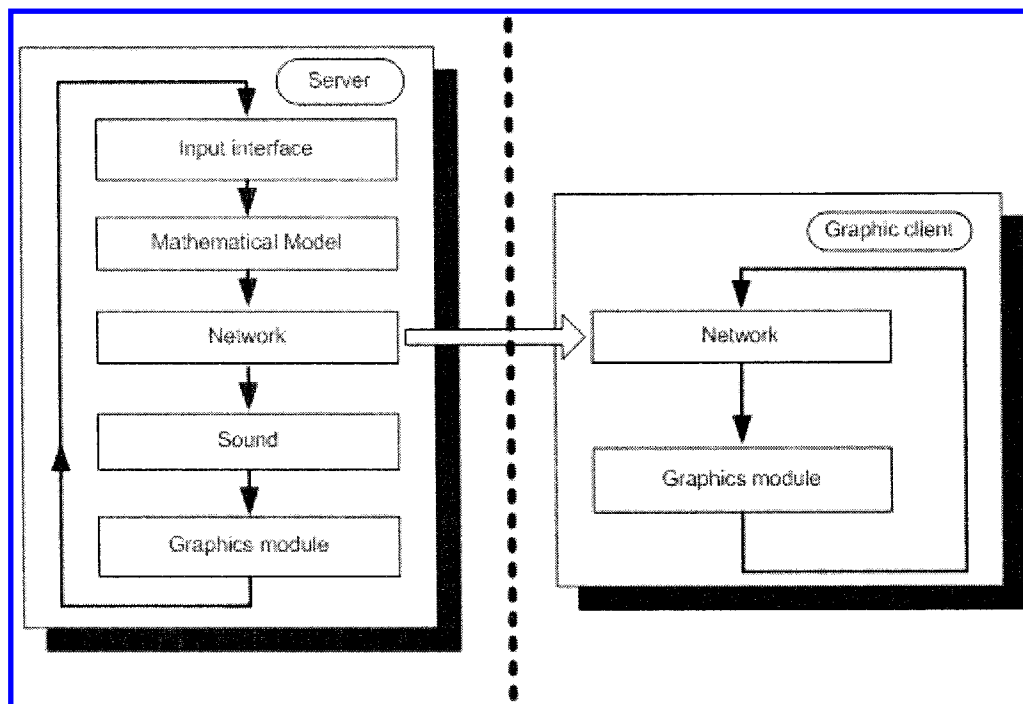
Figure 4. *Tasks in the cluster of PCs.*

In this way, the users feel surrounded in a 3D sound space that complements the visual space. The ambient sound is generated from a traditional song of the cathedral, mainly breaking for the directional sound of the Botafumeiro when it cuts the air with its swing. Figure 4 shows the main loop of the engine. The platforms used are Pentium III 500 Mhz, with a graphical subsystem based on the chip Geforce 256 of Nvidia with sound cards described before only in the server.

The projector equipment is made up of six standard LCD or DLA projectors. The light emitted by the projectors is polarized to use stereo projection with passive glasses.

The scene is the interior of the Cathedral of Santiago. The model has been cast from blueprints given by the "Consorcio" de la Ciudad de Santiago de Compostela, both from CAD and from original blueprints. High-resolution digital cameras have been used to capture the textures of walls, columns, and, in general, any element forming part of the scene. The user's standing point is that where the Tiraboleiros stand, close to the main altar, in the cross of the cathedral.

5   Interface

Interface design is extremely important because it defines the communication between the user and the virtual environment. It has been designed as a metaphor between the real system and the interface. As has been mentioned previously, pulling the Botafumeiro's rope increases and decreases its length, ΔL, and consequently the energy of the system. Therefore, the user or users must perform this pulling process with some kind of interface. In real life, the Botafumeiro's rope is wound around two rollers, of different diameters at the end of a structure that supports the censer, thereby linking the Tiraboleiros and the Botafumerio. This structure is composed of four corbels starting at the great crossing piers, in iron frames in which they end and where the rollers are installed. Wooden guides help maintain the plane of the oscillation. Two rollers are used for the propose of the multiplication of the length of the rope pulled. When we analyzed this pull system, we found no commercial interface that can be used for this application. Thus, a new interface had to be developed.
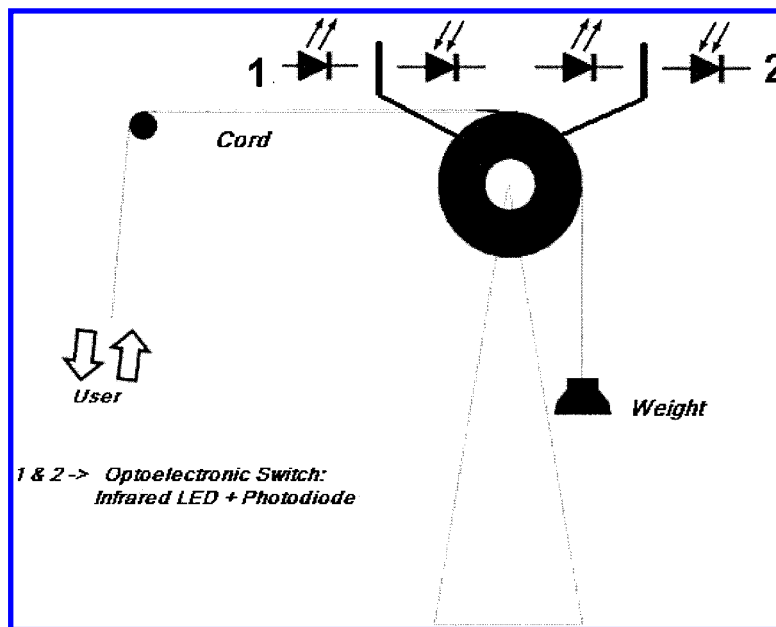
Diagram 1. *Botafumeiro pulling interface.*

The interface we developed tries to imitate the real pull system. The interface is composed of a rope and a roller (diagram 1). A set of sensors, situated on the roller and the support structure, allows the user to know when the rope is pulled, the length pulled, and the speed of the pull (although this last parameter is not used in the equations). The computer is linked with the interface by the joystick port.

An important element of the discussion is whether an interface with force feedback is necessary. Although we logically think that the tension of the rope could be used by the Tiraboleiros in a learning process to calculate the point of pull, this is not true. As we explained before, the Tiraboleiros pull when the Chief orders, so their perceptions are not involved in the pulling process. In this way, the team works independently of their senses. The force feedback proportional to the tension is not really necessary, and therefore a fixed feedback was included in the system by a weight at the free end of the rope. Nevertheless, the mathematical model allows us to know the tension of the rope and it will be possible to use it in the future by a modification in the interface.

6 Conclusions

In recent years, the PC, the efficiency of the new graphics accelerator cards, and the sound equipment have increased dramatically. As a result, they can be used to develop immersive or semi-immersive large displays with high sound and image quality on PC platforms.

We have presented an implementation of this kind of system and a complex application on it. The system has high image and sound quality, which allows us to conduct an important stimulation of the visual and hearing senses, and therefore an important degree of presence too. The architecture allows us to cover the user's angle of view with stereo image and stimulate the hearing sense by 3D sound space.

The system uses an evolution of the NAVE architecture by the modification of the projection system and the inclusion of a new interface with the user. The modifications increase the frame rate of the system and the resolution of the screen, and decrease the global price of the projectors.

The application developed is a virtual environment of the interior of the Cathedral of Santiago de Compostela and the simulation of the Liturgy of the Botafumeiro. For this simulation, a singular user interface and the reso-

Figure 5. *The system (laboratory picture).*

Figure 6. *Virtual Tiraboleiro.*

lution of the mathematical model of the movement of the Botafumeiro has been developed. The interface simulates the tasks of the Tiraboleiros, allowing the users to become an element of this old tradition that in another way would be impossible. The manual control and the locomotion procedures of the interface are learned quickly by the participants. In this way, seventeen users, older than eighteen and with technical university studies, have been the object of an experiment to evaluate the learning process of the pumping protocol. Sixteen users did not perform the pumping process correctly, but these results were expected for several causes. Although they can know the position and the speed of the Botafumeiro, they cannot use previous experiences to compare and apply it to this system. In this way, the problems with the movement of the system presented by tradition are repeated in the virtual system again. (See figures 5 and 6).

When the user is informed of the pulling technique, he can obtain a much better movement of the system. The participants use visual and sound references to determine the position and speed of the Botafumerio. The visual sense is used when the Botafumeiro is far away (maximum angle) but, when it passes near the participant (zero angle, maximum speed), he or she mainly uses the hearing sense to determine the maximum speed and maximum sound of the censer because of the whistling effect. In this way, an interesting conclusion is that the immersion of the system allows the users a proper functioning, giving them a correct stimulation of their senses.

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