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RECREATING THE AMOEBA VIOLIN USING PHYSICAL MODELLING AND AUGMENTED REALITY

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ABSTRACT

The Amoeba violin is a bowed string instrument present at the Danish Music Museum in Copenhagen. The instrument is not played anymore due to its unpleasant sonorities and uncomfortable shape. In this paper we recreate the Amoeba violin using extended reality technologies and sound synthesis by physical models. We design and evaluate two applications that can be used either at the museum (augmented reality version) or at home (desktop version) to learn about the history of the instrument and its sonorities. The app was created for the Danish Music Museum, Musikmuseet, located in Copenhagen, in response to the demand for reduced contact of shared surfaces and official calls to stay indoors that followed the COVID-19 outbreak in 2020. User testing on both versions shows that they both are considered easy-to-access and educative, however the AR version was more favoured overall.

1. INTRODUCTION

It is relatively recently that the experience of visiting a museum started diverting from its traditional meaning. Since the establishment of the museums as institutions up until the beginning of the 21st century, the visitors were generally expected to wander the exhibition grounds, while passively taking in the information that the curators had planned to provide them with [15]. This offered minimal chances for interaction and, ultimately, led to low visitor engagement [12]. In the last couple of decades, however, a growing number of museums around the world have enriched their exhibitions through the use of digital media, aiming to make the visit more engaging and memorable. As Brown argues in [4], implementing technologies like Virtual Reality (VR) and Augmented Reality (AR) is largely beneficial to cultural heritage sites, especially in communicating their product to younger audiences. AR applications are an affordable solution that can work very well in limited spaces, as modern mobile phones are powerful enough to support such technologies, and no extra spaces are required for its implementation.

Figure 1. A photograph of the Violino Arpa or Amoeba violin owned by the Danish Music Museum and a 3D visualization of it.

A few years earlier, in 1997, Feiner et al. [9] and Rekimoto [22], had already seen the potential uses of Augmented Reality (AR) for cultural applications. It wasn't long until the technology took off. One of the earliest example of a complete AR application for a cultural location was implemented at the archaeological sites of Pompeii, Italy [23], and Olympia, Greece [**?**] in 2001. That system, though primitive in its design and equipment, was rather powerful for its day and produced fairly believable results. This is confirmed by the generally good reviews those systems received from their users [19]. Since then, AR has been constantly gaining ground as an educational tool in the heritage sector. In fact it seems that there is a stronger tendency for the implementation of AR applications than for VR applications [1]. In this paper, we aim at using AR to reconstruct an instrument from the Danish Music Museum in Copenhagen, the Amoeba violin (see Figure 1). This instrument 's sonorities were not considered as pleasant, so the instrument was not adopted (maybe also for its ergonomic). In order to recreate the sound of the instrument, we created a physically based simulation together with an interactive application that describes its history. We tested the application in both a desktop version and an AR version.

2. DESIGN

We designed an interactive application that aims to entertain the Danish Music Museum potential guests, providing educational information about the Amoeba violin also known as Violino Arpa (Fig. 1), a distinguished instrument that is an indivisible part of the museum's exhibition. It consists of two different versions: the AR and the desktop version, which we are going to compare and examine. The set up for running these two applications is comprised of an Android smartphone and a laptop.

2.1 Design considerations

The application elaborates on multiple characteristics and aspects of one of the most significant exhibits of the museum. The instrument's funky shape and history seem to be an attraction for the Danish Music Museum, which acted as an inspiration point for the concept development of the application. The application aims to familiarise the user with the instrument through the use of extended reality technologies, enhanced visual representations, and digital sound synthesis. In an attempt to provide a brief but concise set of informations to the user, much like a typical museum visit would, we decided to organise the app in four stages (scenes) into which the user can navigate in a linear fashion. Three of those scenes correlate to the key areas that would be of interest regarding an historical musical instrument: its look; where the user has a chance to explore the shape of the Amoeba Violin in detail, its history; where facts regarding the background of the instrument are presented, and its sound; where an interactive musical player offers the chance to listen to the sounds of this unusual instrument. With regard to the amount of historical context offered, that is purposefully kept short and built around a story.

In addition to the aforementioned scenes another one was created, where the user is called to put together pieces of an Amoeba Violin in order to create a complete instrument. In fact, this is the first scene the user encounters on opening up the application; a design decision made in order to increase engagement. Each one of the four scenes fulfills a unique role that solidifies the above while attempting a fun approach.

3. IMPLEMENTATION

The app was built using Unity3D [27]. The sound of the Violino Arpa is extremely hard to find, as the instrument was an unsuccessful experiment. Therefore, all of the sounds that are added in the application are simulations of what the instrument sounds like. Those simulations were designed in MATLAB and implemented in real time using C++ and the JUCE framework [17].

3.1 Physical modelling synthesis

The Violino Arpa is unique instrument that is fortunately preserved at the Danish Music Museum in a good condition. However, due to its age combined with this desire for preservation the instrument cannot be played by the general public and recordings of its sound do not exist. This only leaves the possibility of a simulation of its sound, based on the physical properties and behavior of the instrument. In fact, the behavior of music instruments can be described by partial differential equations (PDEs), which describe the rates of change of certain variables of the considered process such as time or spatial position for instance. Solving these equations can take different routes with various degrees of complexity (and accuracy). There are certain techniques that can convert these PDEs to systems of equations which can be solved by linear algebra techniques, well suited for computer processing. These are called numerical analysis techniques, one of which is the Finite Difference Method (FDM) and was the choice for solving this physical system.

Figure 2. The view when one enters the desktop application, which is an imitation of the staircase of the Danish Music Museum.

The physical system used to model the Violino Arpa consists of a bowed stiff string, rigidly connected to a resonant plate. The PDEs describing this system in continuous time are given in Equations (1) to (3) and follow definitions from [3]. The displacements of the string and plate respectively are noted as $u(x,t)$ and $w(x,y,t)$. Furthermore, the subscripts t, x and y denote differentiation with respect to time, and the 2-D spatial coordinates.

The bowed stiff string is described by

$$\begin{aligned}\rho_s A_s u_{tt} = T_s u_{xx} - E_s I_s u_{xxxx} - 2\rho_s A_s \sigma_{0,s} u_t + \\ 2\rho_s A_s \sigma_{1,s} u_{txx} - J_B F_B + J_{C,s} F_C,\end{aligned} \quad (1)$$

with material density ρ_s [kg/m^3], cross-sectional area $A_s = \pi r^2$ [m^2], radius r [m] tension T_s [N], Young's Modulus E_s [Pa] and area moment of inertia $I_s = \pi r^4/4$ [m^4]. Moving on, $\sigma_{0,s}$ [s^{-1}] and $\sigma_{1,s}$ [m^2/s] are coefficients introducing frequency-dependent and frequency-independent damping respectively. Furthermore, F_B is the bowing force in [N] while J_B [m^{-1}] is a distribution function describing where the force is applied on the string. Finally, F_C is the connection force (via the rigid connection to the resonant plate) with $J_{C,s}$ [m^{-1}] describing the spread of the connection force.

The resonant plate is modelled using the Kirchhoff thin plate model with losses. Using the 2D Laplacian which when applied to w is equivalent to $\Delta w = w_{xx} + w_{yy}$ the

PDE can be written as:

$$\rho_p H_p w_{tt} = -D_p \Delta\Delta w - 2\rho_p H_p \sigma_{0,p} w_t + 2\rho_p H_p \sigma_{1,p} \Delta w_t - J_{C,p} F_C. \quad (2)$$

The physical properties parameters that have been described for the string, are the same for the plate. The difference is indicated by the subscripts s or p. New parameters for the plate not previously described include plate thickness H_p [m] and $D_p = E_p H_p^3 / 12(1-\nu_p^2)$ [kg·m^2·s^{-2}], with dimensionless Poisson's Ratio ν_p. Again, F_C [N] is the connection force over a distribution $J_{C,p}$ [m^{-2}], (the magnitude of the force is the same for the plate and the stiff string, but the distributions can be different).

A perfectly rigid connection is assumed, meaning that at the location where the two elements connect, the displacement is equal. This can be written as

$$\langle u, J_{C,s} \rangle_{\mathcal{D}_s} = \langle w, J_{C,p} \rangle_{\mathcal{D}_p}, \quad (3)$$

where $\langle f, g \rangle_{\mathcal{D}}$ represents the inner product of f and g over domain $\mathcal{D}$. If the connection distributions, J_S and J_P are very localized (a Dirac function for instance), then it means that the connection is at a single location rather than distributed and Eq. (3) reduces to $u_{\text{P}} = w_{\text{P}}$ at some location P.

The boundary conditions, which describe the behavior of the elements at their edges are: simply supported for the string, i.e. $u = u_{xx} = 0$ and clamped for the plate, i.e. $u = u_n = 0$, where n is the coordinate normal to the edge.

Regarding the model used for the interaction between the bow and the string, a complex elasto-plastic friction model is used, capable of describing the non-linear relationship between the two components. This model was first introduced by Dupont [7] and investigated in detail with regards to its application in music by Serafin [24]. Furthermore, it was proved to be implementable in a real-time application by [30], whose implementation is the basis for the current model. These continuous time PDEs can be discretized and thus resolved numerically. This means the continuous system is divided in grid points in space: $x = lh$ and $y = mh$ and samples in time: $t = nk$, with h being the spatial step and k being the time step and $l \in [0, 1, ..., N_x]$, $m \in [0, 1, ..., N_y]$, where N_x and N_y are the number of horizontal and vertical grid points. For simplicity in the case of the plate, the same spatial step is assumed in both spatial directions. Discretizing the model in such a way comes with some downsides, as the accuracy and bandwidth of the solution is dependent on the number of points used to describe the model, with more points giving greater accuracy, but also more information to compute. A caveat, however, is that there is a limitation on the size of the spatial step, h (for a given time step, k). That is, there exists an h_{min}, such that $h \geq h_{min}$, which if not respected, will cause instability in the numerical solution. These stability conditions are not described further in detail here, but the reader is referred to [3]. All the sound simulations of the Violino Arpa have been carried out as close to the stability condition as possible, thus giving a full bandwidth solution, i.e. all frequencies up to the Nyquist frequency can be described. The interesting shape of the Violino Arpa is "sculpted" from a square grid of discretized spatial points to be as close as possible to the real shape. A single string is then added to the system, which is tuned to different frequencies (or musical notes), by adjusting the tension of the string. A simulation is carried out for each tuning of the string at a sampling frequency f_S of 44100 Hz, with the bowing position being fixed at $0.29L_s$ from the left edge. The sound is extracted as the vibrations at the bridge location, where both the effects of the vibrating string and the resonant plate are combined. An overview of all the parameters used in the physical model is given in [27].

Finally, the musical notes of the Violino Arpa were extracted from the simulation. These sounds are being used in the 4th scene of the app, where the user can play the Violino Arpa.

3.2 Using the app

The app consists of four scenes that are largely similar in both versions. In the first one, the puzzle level (Fig. 4), the user sees a Violino Arpa broken down to smaller pieces and has to connect them in order to create a complete instrument. With each correct movement a harmonic sound of the Violino Arpa can be heard, and the pieces snap together. Completion is not mandatory in order to proceed to the next scene; after 15 seconds, the "Next" button appears on the screen, regardless of the success level. The Violino Arpa is now presented in a single piece, with the option to rotate it in 360 degrees. In the AR version, the instrument gets larger as the users approach the poster, offering thus the option to focus in specific parts of it.

The third scene consists of a 2D story made of 20th century engravings. There, the users can scroll and see colour being added to the the black-and-white engravings, while reading some key information about the history of the Violino Arpa.

Finally, in the last scene, the users see a music player, where each circle represents a note of the instrument. They can test different notes, and decide for themselves whether or not they like the sound of it.

4. EVALUATION

The goal of this evaluation was:

- to test how AR technologies and non-immersive desktop applications can enhance the overall experience, cultural appreciation, and educational reinforcement of a virtual museum visit, and
- to illustrate the differences in effectiveness and popularity between the two.

4.1 Participants

A total of 23 subjects, 12-39 years old (Mean:28.4, Std Deviation: 4.73) took part in the research experiment. All of them had experienced in the past non-immersive applications while less than 30% had experienced AR applications.

Figure 3. User interacting with the mobile application (top) and online version (bottom). In the AR version, the subject is located at the entrance of the Danish Music Museum where posters of the musical instruments are placed. The participant is playing with the notes of the Violino Arpa.

4.2 Procedure and Task

The participants were split into groups of 2, and were invited to the Danish Music Museum. Before the testing began, they were briefly informed about the idea behind the different versions of the app, and the setup (smartphone/laptop) was explained. They were encouraged to explore the application without seeking instructions, except from those given inside the app.

Subsequently, one of them went to the museum entrance to test the AR version using a smartphone (Fig. 4), while the second one went to the reception to test the desktop version of the app. When they finished, they switched places, in order to try the other version of the app. After the testing, all participants had to complete a questionnaire, answering about the experience using both of the application versions, and the comparison between them. The experiment duration was 30 minutes for each group.

4.3 Measurements

Self-reporting measurements were used in combination with mini-interviews, recording, and think-aloud notations.

The items of the questionnaire were divided into three categories: Online version, Mobile version, and a comparison between the two. The specific terminology was used (Online/Mobile) to describe the two versions of the app, in order to be more understandable and less confusing for the participants. These three sections have the same 9 questions concerning the functionality, efficiency, interactivity, and usability of the application.

Figure 4. A screenshot from the application where the participants explore a puzzle with the components of the Violino Arpa.

5. RESULTS

5.1 Quantitative Data

As an overall review of the data, most participants seem to enjoy both experiences (Fig. 5 part A & B). Over 70% of the subjects felt that both applications, AR and online, were interesting, easy to use and they would like them in the context of a museum. Around 65% of the subjects seemed to be eager to explore the Danish Music Museum after using the applications. The same amount of participants also stated that this experience had some educational benefit. However, the application was lacking in embodiment and continuity of narration. Over 60% of the participants stated that it would be easy to access both applications, with regard to the COVID-19 pandemic outbreak. In the last section of the questionnaire the participants were asked to choose between the two different versions of the application. Fig. 5 (part C) visualizes the rest of the gathered data. As an overview of the collected information, the Augmented Reality (mobile) application seems to be preferred over the desktop application. No difference was recorded in terms of narration, educational content, and accessibility between the two versions. Around 30% of the participants felt that the mobile application gives you a better activation of the body use.

5.2 Qualitative Data

The overall review on the participants' impressions was very good. The experience of both applications was described as "amazing", "interesting", "practical", and "genuine" (especially for the mobile application). A lot of people thought that it is a smart way to make people create new memories, containing an educational aspect that they will remember. During testing, most users performed similar actions. A large number of them was not sure what to do when coming across the puzzle pieces and asked for guidance, but after connecting the first piece thought it was a fun idea and excitement started building up. There were

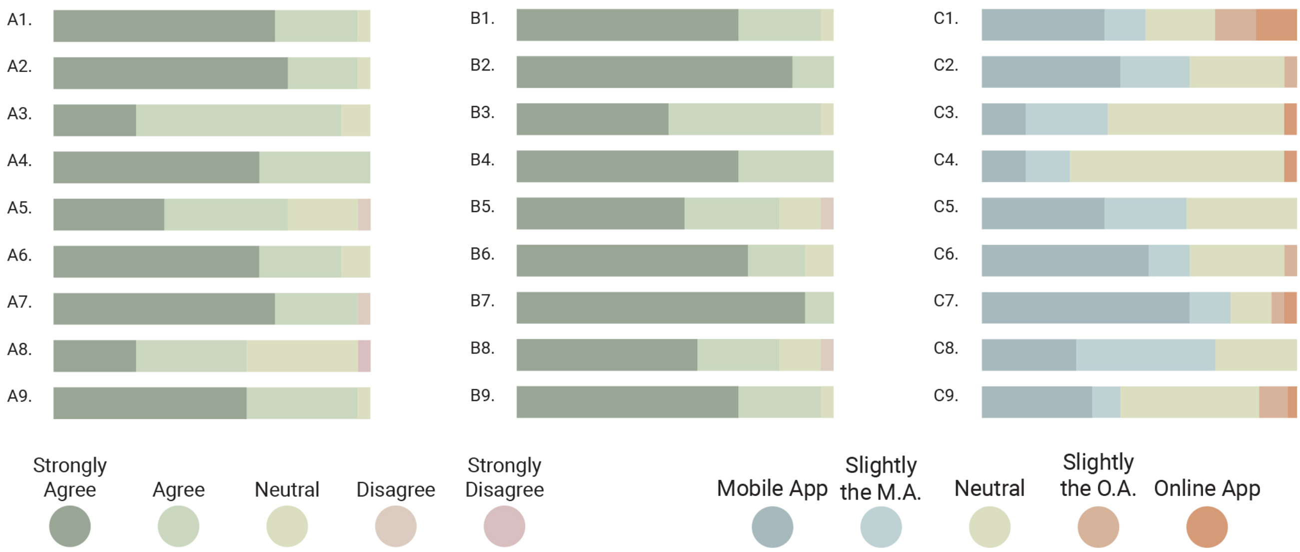

Figure 5. Visualization of the quantitative data that has been obtained from self-report measurements.

also many comments about the music player scene. Participants expressed a strong will to have the names of the notes stated next to the circles, so that they would be able to play short melodies. Also, many of them pointed out that it would be better if the buttons were activated with touch (in AR) or hovering of the mouse (in the desktop version) to increase the continuity of the sound(s). One subject commented on the look of the player, saying it is too abstract and it looks more like an optical illusion, rather than something that could play music.

5.2.1 Observed Actions

Beside the aforementioned initial uncertainty in the first scene, it was also common for users of the AR version to rotate the smartphone instead of the model of the instrument, due to the single "Rotate" instruction in the second scene, which many of them found too vague. Another common occurrence, but for users of the online version, was to try and scroll down in the third scene - the history of the Violino Arpa. Even though it works, it moves rather slowly. Therefore, they often had to be told that it's easier to go through this scene using the mouse buttons. Finally, the music player was the scene that majority of the participants spent most of their time, most of them just playing and making comments on the quality of the timbre, and some of them trying to figure out the notes and compose a melody.

6. DISCUSSION AND CONCLUSION

The limited number of test subjects affects the accuracy of the results. A recurring comment throughout the testing session was about the lack of information provided with regard to what is expected of the user in each scene. Although the intention was to keep the amount of text minimal in order to allocate more space for the visual elements, it turned out that the subjects required more details, and reported that both verbally and in writing. Another common comment regarded the interaction during the first scene of the online version. Several participants found the way they were moving inside the virtual space too similar to popular game. Though unforeseen, we ascribe this impression to the first-person camera approach.

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