Smart Cultural Site: an Interactive 3d Model for those with a Visual Impairment

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Abstract. We developed a prototype of the square where the Leaning Tower of Pisa is located as an intelligent 3D interface system that improves the accessibility and usability of cultural sites for everyone, including people with a visual impairment. We combined tactile information with audio tracks to enable potential users to explore the artifact autonomously. We exploited low-cost and partially open-source technologies thus rendering our system easily replicable. First, we designed various 3D source-based models to be printed with an additive manufacturing technology. Next, the 3D prototype was linked to a Raspberry in order to enrich the tactile exploration with an interactive audio guide. A preliminary evaluation of the proposed system was conducted in order to refine its design.

1. Introduction

Modern technologies of rapid prototyping (RP), which enable an object to be reproduced from a 3D model, offer new opportunities for providing access to the cultural heritage for all. Compared to traditional techniques, such as gypsum casts, thermoformed boards, tactile patterns obtained with RP and 3D printing technologies speed up and improve the reproduction of models.

Having 3D models of statues, buildings or floor plans and layouts is more appropriate for users with special needs, such as visually impaired people, who rely on the sense of touch to perceive objects. Tactile models enable the visually impaired to obtain information on fundamental details, such as 3D shapes and surface textures. However, as demonstrated by Hayhoe [6], tactile 3D models may be not enough to fully enjoy exploration and perception of content, especially for multifaceted objects. The correct understanding of a 3D reproduction is affected by personal skills, size of the model (compared to the original), reproduction details and the overall quality of the tactile model. Specific details are often missed by the visually impaired due to the limitations of the model.

Some types of information cannot be reproduced in a tactile way. Combining a tactile model with audio tracks can help the visually impaired to build a better mental picture of the whole artwork.

In this paper, we propose a model which provides a multimodal interaction to explore artistic and architectural 3D models. To illustrate our idea, we present a working prototype made up of of 3D models developed using source-based modeling [4] and RP. The models is equipped with buttons that are modelled in a 3D format and activate descriptive audio tracks. The shape of the button indicates a specific type of information. Tracks can also be easily interrupted and reactivated. The prototype is built with low cost components and uses a Raspberry PI 3 to connect each button to a Python script that manages and plays the audio tracks.

Although several studies have investigated interactive tactile prototypes that enable art works to be explored by visually impaired users, most do not consider 3D interactive modelling. For instance, [9] investigates a combination of vibration and speech feedback which can be used to make a digital map on a touch screen device more accessible. In [13], the authors created a prototype of a tactile-audio map based on a combination of tactile hardcopy and an SVG file used together to provide interactive access to a map image through a touchpad. The result is a tactile-audio representation of the original input image.

These projects, along with similar ones presented in [1] and [12], propose interactive tactile approaches that are not based on true 3D models, since they adopt a 2D touchable format in which the representation is basically 2D with some parts in relief.

In our study, instead, we combined a 3D modelling approach with audio descriptions in order to enrich the visually impaired user's interaction. This paper proposes a working methodology aimed at developing interactive interfaces of artistic objects or cultural sites. The methodology is easily replicable, and can improve the cultural experience of a visually impaired user while increasing their autonomy. In short, we propose an enriched and interactive tactile model for the visually impaired with particular attention to details, which can be useful for touristic and educational purposes. Various issues are overcome that are typically encountered when exploring the tactile models available on the market, such as those reported in [3], [15], [16].

The main issues can be summarized as: a lack of detail (some important details are missing in the reproduction), replicability by specialized centers (high costs), lack of choice in selecting information types, and free exploration using both hands. Specifically, our approach is characterized by:

1. *Low cost and replicability*: easy to reproduce for other sites and objects at a low cost.
2. *Avoiding unintentional selection*: many visually impaired like to explore a model with both hands and without restrictions [7], [8], which may not be feasible when sensors are embedded within the model itself.
3. *Semantic information and on-demand selection*: buttons with different shapes are proposed for activating different types of information (historical, architectural and practical). An artefact is usually associated with a single audio track that describes all the information and requires listening to in its entirely. In our model, the user can select the level of detail of the description by choosing from a set of audio tracks that give listeners an increasing level of detail.

The paper is organized as follows. Section 2 discusses related works. Sections 3 and 4 give an outline of our methodology. Section 5 describes our interactive prototype. Section 6 briefly describes the preliminary evaluation with visually impaired users. Section 7 concludes the paper.

2. Related work

Although there are many projects using a multimodal interaction that are aimed at enabling the visually impaired to increase their access to cultural contents, few use 3D modeling. Tooteko [3] is based on a smart ring that enables users to navigate a 3D surface with their finger tips and thereby to access an audio content that is relevant to the part of the surface that they are touching at that moment. The system has a high-tech ring, a tactile surface tagged with NFC sensors, and an app for tablets or smartphones. When the ring reaches a NFC sensor, it communicates with the app in order to activate the audio track. The 3D models are built using standard 3D printing. Hotspots are inserted inside the model, which needs to be reasonably large to accommodate them. They also need to be at a reasonable distance to be clearly detected by the reader. Hi-Storia [15] proposes a similar approach.

In both these projects, the sensors that trigger the audio tracks are integrated within the model itself. This has important drawbacks. First, while listening to an audio track, the user can easily jam into another hotspot, thus stopping the current track and triggering a new one. This is annoying for users since visually impaired people often use both hands when exploring a 3D object and listening to audio tracks [7], [8]. Moreover, integrating sensors within the model is very costly, which may be prohibitive for small museums. Finally, these approaches entail the presence of an external person who has to explain to the user how to move and what to do before starting to explore the model.

A different approach is proposed by 3D Photoworks [14]. Color images are printed directly on the relief surfaces and infrared sensors are integrated into reliefs. Their interactive tactile prototypes accompanied by audio guides are based on motion capture [2], [10]. Depth cameras, placed above the tactile template detect the movement of the user's hands. The main disadvantage of such hand tracking systems is their cost and complexity. Technologies are continuously improving and becoming cheaper, however, the current low-cost trackers are not very accurate. For example, while slow movements and limited rotations of the hand are usually traced effectively, when the speed increases, the position of the hand is easily lost and users can become very frustrated.

Despite their limitations, all these systems represent an important first step towards effective access to cultural sites using tactile interactive models. Our approach tries to overcome these problems through a low cost solution, and by moving the audio track activation outside the 3D model, yet still using low cost sensors for activating the tracks.

3. Our Approach

Our approach consists in reproducing an interactive 3D model by combining tactile perception with audio tracks to explore the floor plans of monuments, rather than the external structure of the buildings. This is due to the lack of floor plans and reproduction of indoor monuments that are perceivable by touch. Likewise, tactile reproductions usually lack specific details especially those too small in the reproduction scale chosen. These types of reproduction (floor plans and specific details) can, in fact, be very useful for learning and perceiving details that are evident to sighted users. However, our approach can also be adopted when reproducing the outside of buildings.

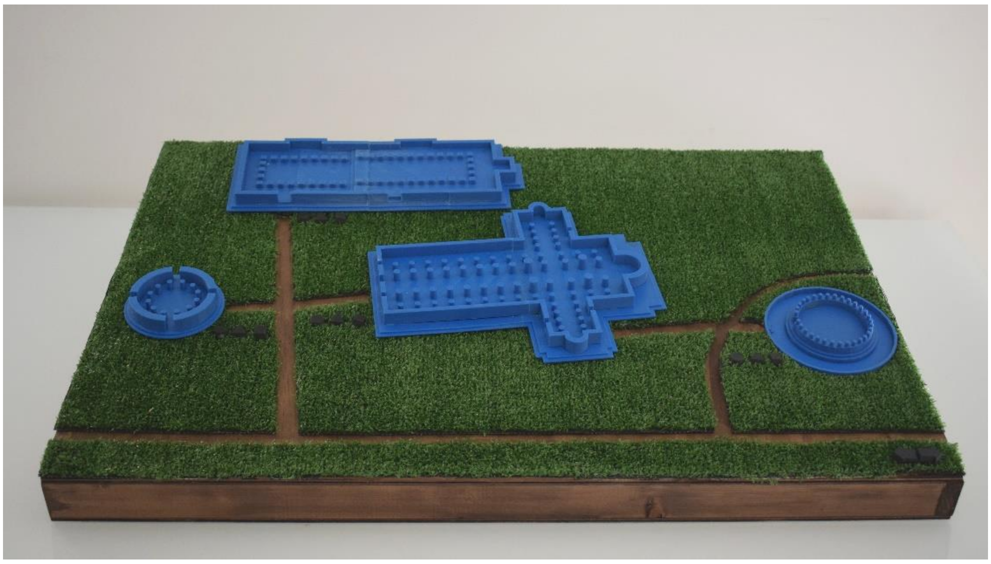

Figure 1. The 3D prototype of Piazza dei Miracoli

We applied our approach to a tangible 3D model of the four monuments located in “Piazza dei Miracoli” (home to the Leaning Tower of Pisa, Italy). The challenge was that each monument has a different floor plan: (1) the central floor plan of the Leaning Tower and the set of columns on the outside; (2) the Latin cross layout of the Cathedral; (3) the rectangular layout of the Monumental Cemetery; and (4) the central floor plan of the Baptistery. When visiting Piazza dei Miracoli, the arrangement of the various buildings in the square and the walkway that links them are clearly visible for a sighted person. Our goal was to deliver a similar perception of this overall arrangement for the visually impaired. The reproduction of each monument is built considering a two-dimensional plane which cuts the monument at a height of approximately 1 m (3.28 feet) from the ground. We were thus able to show the section of the perimeter walls and of the columns which are key to understanding the overall architectural setting (see Fig. 1). This tactile reproduction enables visually impaired people to perceive the thickness and position of the columns, the fact that the central nave is higher than the side naves, the position of different sets of arches, and so on.

4. Methodology

In building our prototype, we followed guidelines and standards for tactile graphics [5]. These guidelines however, refer to the construction of 2D models, thus we devised and added rules especially related to 3D. For instance, while working alongside some visually impaired users, we noticed that there is a minimal distance between two 3D objects (e.g. columns) which needs to be maintained so that they are perceived correctly by a finger tip touch . Our system is built using source-based modeling [4].

A 3D model can be obtained using two different approaches to represent the structure of the artwork (monument, statue, etc.): (1) reality-based, such as via laser scanning or reflex camera; (2) source-based, via a digital representation of a work using computer graphics. Through this second approach, we can also model a work that no longer exists, or that has only partially survived, and whose reconstruction is based on historical sources. The approach used depends on the characteristics of the work and on the goal of the project. When using 3D modelling for very large monuments, as in our case study, the artwork is simplified for a small-scale reproduction (unimportant details are not included). We thus used a source-based approach, which is faithful to its original architectural plan and to the historical facts, and we decided not to reproduce details that might not be easily perceptible by touch.

Starting from the digital model, the tactile models were produced through digital fabrication techniques. To model a source to be printed we: (1) obtained the floor plans in 2D; (2) modelled a 3D version based on the scale and the official sources (e.g. a circle on the plans is a cylinder in the 3D model); (3) selected a simplified style for the plans, i.e. without architectural details; and (4) reproduced various architectural style details. The appropriate scale resolution and size of the details was decided in collaboration with visually impaired people throughout the design-development cycle (see Section 5).

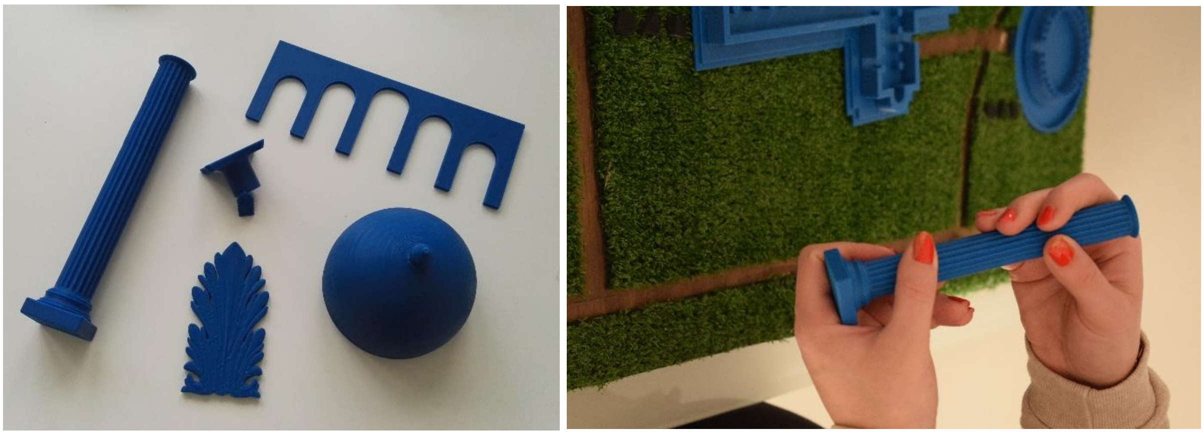

Figure 2. The architectural elements (left) and their size compared with the main model (right)

For the 3D printing, we used an additive technical process in which the object is produced by the gradual accumulation of material [11]. The 3D prints were made with a Fused Filament Fabrication printer (FFF) which melts and extrudes a thermoplastic filament, in our case acrylonitrile-butadiene-styrene (ABS), an oil-based plastic. The model sizes were chosen to ensure a good exploration of the relevant details according to our participatory analysis. We used Blender to develop the models and a proprietary software for slicing on the printer, a Zortrax M200 (available in our laboratory, cheaper printers can also be used). Because of the technological limitations of the printer used, for some of the models, such as the Monumental Cemetery or the Cathedral, we had to divide the model and print it in separate pieces glued together in postproduction. We also created 3D models for specific details of the monuments that are relevant to understanding the overall structure, such as the dome and the nave profile of the Cathedral, and a Corinthian column representing the main architectural style of the Cathedral, the Baptistery and the Leaning Tower (see Fig. 2). Reproducing these details is very important since they cannot be perceived by a visually impaired user.

Decorations were not reproduced directly on the 3D model of an architectonic detail due to the scale limitation. However, some decorations are fundamental for the overall perception, such as the acanthus leaf in the Corinthian style column capitals. In this case, we produced a detailed model of the decoration, in a different scale, and printed it separately. For instance, the acanthus leaf was printed on a larger scale with respect to the capital. The architectural details and the decorations printed separately are located on a panel placed near to the main model of the square (Fig. 3). Each detail is introduced and described in the architectural audio track, whose reproduction is triggered by the circular shape button .

We can summarize the reproduction procedure in the following phases: (1) Simplification and preparation of the digital models; (2) Selection of the details to be reproduced in a larger scale; (3) Print, refinement and assembly of the models; (4) Design of semantic touch buttons and preparation of audio tracks; and (5) Development of an interactive model (e.g., using Raspberry or Arduino). We describe all these steps in the following section.

5. The interactive 3D prototype

Our model is designed to render users entirely autonomous in their exploration of an artwork. To meet this aim, each piece of information is provided through both tactile and audio information. The visually impaired can explore the model by touch and to activate an audio description related to a specific monument/detail. Spoken descriptions are organized into several audio tracks, which can be recorded by a person or via voice synthesizer through a specific audio content generation application, such as DSpeech[11] or Balabolka[11]. This means that the content can also be in different languages.

Figure 3. Panel with the architectural elements

The device used to manage the interaction user-3D model is a Raspberry PI 3, a single-board computer that is a few centimeters wide, with general purpose input/output capabilities. The Raspberry is fixed below the prototype. Aural descriptions are activated by buttons placed next to each model (e.g. near the main entrance of each monument in Fig. 4). Buttons are connected to the Raspberry with cables. In our prototype, each model has three buttons which are close enough to be detected without moving the hand. These are easily detectable via their shape which indicates a specific type of information: (1) circles for practical information, (2) triangles for historical overviews, and (3) squares for architectural descriptions.

For each type of information, there is a set of aural tracks. All tracks can be activated with the same button. The first time the button is pressed, an introductory track is activated, which gives general information on the monument. If the users are interested in more detailed information, they can press the button again to listen to the second track, which provides more details. In general, each button is associated with a set of aural tracks ordered according to the level of detail. Each time a button is pressed it stops the current track and starts the following one in the sequence. Users can thus choose how to explore each monument according to their interests and to the time available.

When the user approaches the model of the Piazza dei Miracoli, two proximity sensors activate a welcome audio track explaining how to interact with the model. The sensors are placed in front of the prototype, and compute the distance between them and an obstacle in front of them. When a new obstacle (a visually impaired user) appears within a distance of between 0 and 50 cm, the sensors send the Raspberry the information and the welcome audio track is activated. The user can then decide the times and how to interact with the other audio tracks. The current track can also be suspended by pressing a pause button placed at the bottom right of the prototype.

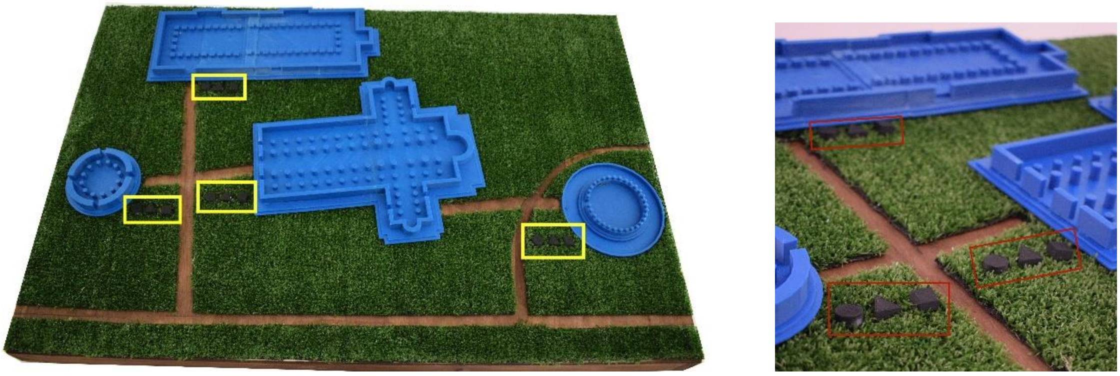

Figure 4. The position of buttons near main building entrances (left) and detail of Cathedral and Baptistery (right)

6. Evaluation

The Our prototype is designed to be an interactive system that can be used by everyone, but is especially useful for the visually impaired who are able to ‘see’ a monument or a detail only via the sense of touch. We firstly evaluated our prototype with a group of three totally blind or low vision users in order to evaluate whether combining tactile interaction with audio tracks is appropriate and intuitive for a visually impaired person. We evaluated the following aspects:

1. The appropriateness of the 3D models in terms of size, shape, texture and scale perceivable by touch;
2. The suitability of the audio tracks, i.e. the level of detail of each track, the problems encountered to activate them, the use of the buttons, and so on;
3. The difficulties encountered while exploring the models and using the audio tracks.

The visually impaired users were involved during the design-development cycle in order to fine tune the details of the prototype before a formal user test. The users firstly familiarized themselves with the model and then informally expressed their impressions and perplexities. We guided their reviews with the following questions:

- *Are the monuments clearly perceivable by touch?* The aim was to understand whether the sizes and shapes were appropriate and if the reproduction by the 3D printer was of a reasonable quality.
- *Are the audio tracks useful, clear and easy to follow?* The aim was to understand how effective the audio tracks were for the user.
- *What about the interaction with the model?* The aim was to gain feedback on the interaction modality used to explore the prototype. Impressions and comments on audio track activation, button shapes and sizes, details reproduced in 3D, and so on were included in our investigation.

Two members of our research team observed the users while interacting with the prototype. This enabled us to collect further information on various interactional aspects that were not mentioned by the users. Regarding the first question, the comments were very important in deciding on the correct size of the models of monuments and details. One user observed that the sizes of some of the spaces left between the columns were not easily perceptible by touch. Other users suggested reproducing some details (e.g. the arches) in a larger scale in order to improve their perception. One user observed that the angle of the base of the Leaning Tower did not reflect reality. All the users suggested reproducing more details in separate 3D models, since it is not easy to get information and 'see' a 3D version of small objects, especially the small architectural decorations. They reported that 3D models usually reproduce monuments and artworks as a single model, neglecting important details due to the scale.

Regarding the second question, the users suggested having multiple audio tracks on different kinds of information. Users could then choose to listen to the amount and type of information that best suited the time they had available and their interests. Accordingly, for the final model, we prepared three different types of audio tracks including architectural, historical and practical information. Each type of information was also divided into different audio tracks with different levels of detail.

In terms of interaction, we observed that the visually impaired users searched for the buttons in specific positions; for example, we noticed that the users tried to find the buttons for activating the audio tracks in the same place for each monument. The users clarified that placing buttons consistently in the same position with respect to a monument would make it easier to find them (e.g. always placing buttons on the right of each monument). We thus decided to place the three buttons near the entrance of each artwork in the model. This was because space limitations made it impossible to place them to the right of each artwork as suggested.

Concerning the shapes of the buttons, the users reported that they were well perceived, and found the audio tracks very useful. We then discussed the idea of having different tracks with different levels of detail. The discussion then moved on to how to manage these types of levels. There were two proposed solutions: (1) two additional buttons to be placed in a fixed position to trigger the 'previous' / 'next' track to the current track ; (2) navigation among tracks by pressing the same button to stop the current audio track and trigger the following one. For example, pressing circles triggers a track with general practical information (the first level), and when pressed again triggers a more detailed audio track. After a short discussion, all the users opted for the second proposal. We thus used only one button in the final version of our model. The users' comments and observing the users in this informal test, thus enabled us to refine our prototype. We are currently working on a more extensive and formal user test with totally blind and partly sighted people.

7. Conclusions

We have presented a novel approach to guiding a visually impaired user in an interactive exploration of a cultural artwork. The approach is illustrated through a working prototype of Piazza dei Miracoli, the square in which the Leaning Tower of Pisa is located. Our approach considers indoor elements rather than all the external monuments as well as specific details of the artworks. The aim was to provide free model exploration with two hands. Our simple interaction model is based on buttons with different shapes to activate different audio tracks. In the future, we aim to evaluate our approach with both sighted and non-sighted people by a formal user test.

Currently, the prototype is conceived just for one individual user at a time, which is a limitation of most such technological devices (e.g. Leap Motion or viewer like Oculus Rift, HTC Vive, etc.). We are thus planning to develop a multi-user system. Our final goal is to design an interactive system that is able to transmit both architectural details and emotions, as happens naturally for sighted users.

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