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Digitizing and navigating unaccessible archaeological sites on mobile devices

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***Abstract* – A very large number of sites, probably the large majority of our Cultural Heritage (CH), are unaccessible to the public due to the lack of infrastructure, improper security conditions or lack of personnel. Digitizing in 3D those sites is not very complicated nowadays. We will briefly review the technology available for cheap 3D digitization, from 3D scanning to cheaper photogrammetric solutions. However, digitization per se is not a solution: 3D models have to be shared in the widest and easiest manner. We will present the design and results of a software instrument that aims at supporting easy navigation of 3D digitized spaces, running on top of mobile devices such as tablets or smartphones. The main goal of this project is to guarantee navigation with ease for users without experience in computer graphics and videogames, while providing high-fidelity rendering of the digital 3D model.**

I. INTRODUCTION

Cultural heritage sites can stay closed to the public due to many different reasons, such as: lack of access infrastructures, location of the site in a private property, an improper health and safety regulations implementation, lack of personnel for guiding and controlling visitors, etc. For example, caves, hypogea, palaces, (underwater) archaeological ruins, underground spaces, etc. typically fall into this *hidden heritage* category. Moreover, the presence of tourists can be a danger for the conservation status of some CH sites. For example, caves with prehistoric paintings can be threatened by an increase in humidity, heat, and microbes brought in by visitors. Therefore, most of those sites will never be accessible to the public, and they can be experienced only through photographs or videos.

The advances of computer graphics and mobile technologies allow us to experience those sites in a much more personal and active way. Therefore, we decided to exploit such progresses to develop a novel approach to the virtual presentation of hidden CH sites. We want to point out that there is a pressing need of technologies able to support:

1. 3D sampling of those hidden and unaccessible CH sites;
2. providing easy virtual navigation of those spaces or artworks, easily accessible to tourists, scholars or students.

Recent advances in 3D digitization technologies have been quite impressive. This domain has quickly matured in the last twenty years, moving from research laboratories to the mass market. Many projects are producing 3D models from normal streams of digital photographs, or 3D scanning add-on for tablets can be bought for less than $500 at the time of writing. We will briefly review the progress and potential of 3D digitization technologies in Section ii.

Our main contribution in this paper is to present the design and performance of a mobile application (app) that allows ordinary users to freely and virtually access hidden CH sites on their personal mobile devices. The app, designed for the Apple iOS platform, allows the user to virtually navigate in a complex space, by means of a very simple and effective user interface. The key is to limit a bit the freedom of navigation to obtain an improved usability. This reduces the complexity of the interface, especially in all those cases where we do not have any complex input device. We present this mobile virtual navigation tool, *VirtualTour*, in Section iii. with details on its architecture. Our approach has been experimented and assessed on two selected CH sites, described in Section iv.

II. 3D DIGITIZATION TECHNOLOGIES

Typically, 3D digitization of CH sites or artworks is performed to create digital models aimed either at documenting the status of preservation at a given point in time, or to produce virtual presentations [7].

Until very recently, the adoption of active 3D scanning was the main option when the goal was to obtain an accurate 3D model, i.e. a metrically correct geometric representation. Accuracy is key to enable us to consider the digital models as a faithful representation. It is a major quality parameter when sampled data should support monitoring and assessing of the possible degradation occurred over time (that can be easily estimated by comparing digital models produced in different times, on the condition that we keep knowledge on the methodologies and operation modes used in the different acquisitions); or when sampled data should support the study and analysis of an

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Fig. 1. On the top left image, the two-levels structure of the Casalrotto church is shown. On the top right image, the church entrance is depicted, together with the first level of the church (bottom-left image) and finally the deeper second level (bottom-right image).

artwork or an architecture.

More recently, low cost techniques for 3D reconstruction based on photographs have shown an impressive improvement in efficiency and accuracy [2] and they are becoming a common resource for many digitization efforts. Current photogrammetric or SFM solutions provide often an alternative to active 3D scanning, under the condition that the data produced bring with them a well documented and precise scaling to the real coordinate space.

Typical active instruments used to digitize architectural structures are still quite expensive; those systems are usually laser-based scanners, called time of flight (TOF) or Lidar scanners. This type of scanners allows the acquisition of complex structures in a short time with an accuracy of 2 or 3 mm, and a sampling rate of one point per squared millimeter (or even denser).

The complete sampling of an architecture is achieved by positioning the instrument at multiple shooting positions. Each shot produces a point cloud corresponding to the portion of the visible surface from that position. Raw sampled data has to be processed to produce the full 3D model of the object/structure; the different processing steps allow switching from raw point clouds or range maps (produced by the instrument) to a global and aligned point cloud (where all data are immersed in a common space), or finally to the final model represented by a triangulated surface (if necessary, with color values assigned to each point or encoded into a texture map).

To illustrate some of the issues faced in a real digitization, let us introduce one of our case studies (see Section iv.). The church of Sant'Angelo in Casalrotto (Taranto, Italy) presents two different and critical conservation issues. The first one is the presence of cracks on its rocky walls; they do not affect the static structure, but have damaged the frescoes (12th-14th century A.D.). The second issue is its high indoor humidity level that is crumbling the walls' surface, damaging the frescoes. For these reasons, a 3D scan of the internal structure was performed with a FARO Photon 120 scanner. This scanner can acquire three-dimensional data with a *ranging error* of ±2 mm between 10 and 25 meters (the ranging error is defined as the maximum error in the distance measured by the scanner from its origin point to a point on a planar target) and with a *ranging noise* (defined as standard deviation of values about the best-fit plane) between 0.4 mm and 1 mm. To produce a model with color information, two different sets of photographs were taken: the first set was used at medium resolution for capturing the color of the whole internal surfaces of the church; the second set of images was shot at high resolution on selected regions, focusing on capturing and documenting the frescoes. This approach has been adopted to generate, in a suitable manner, the color information of a very large 3D environment. Since mapping high-resolution images on the entire church model would have been very complex (both at processing and at subsequent rendering time), the high-resolution photographs have been mapped only to the more significant areas (in this case, the regions holding the wall paintings).

The church is built on two underground floors (see Figure 1), and it has a series of internal columns that make the 3D sampling more complex. For this reason, 25 single shots, totaling 176 millions sampled points, were acquired to sample the entire indoor surface. The point clouds were acquired with an inter-sampling average distance of around 5 mm.

The final model, composed of about 50 million triangles, was created after merging all point clouds. This model reproduces the surface with approximately a sample every 5 mm. This resolution is enough for using it in the future for measuring major conservation problems and to support interactive presentation.

To allows monitoring also more subtle variations, e.g. the ones related to the potential deterioration caused by the weathering, more accurate results could be needed, for example obtainable by selecting some critical regions and sampling them with a more precise instrument (e.g. a triangulation scanner based on light fringes).

III. VIRTUAL NAVIGATION USING MOBILE PLATFORMS

The virtual navigation/presentation of not-accessible CH architectures or artworks can be obtained by either adopting Virtual Reality (VR) technologies or by endorsing the web platform and related technologies (e.g. [6]) or even by moving all data and visualization instruments on mobile platforms. Although in the last years Virtual Reality applications and interactive presentations have begun to spread in the CH domain, their potential is still underused. In literature, there are many examples of the use of virtual reality as a support to the real visit of the museum (e.g. [5]). Some researchers also suggested how to present historical content. Aliaga et al. [1] proposed a framework for digital exploration of CH objects. Some systems, as proposed by Wojciechowski et al. [8], were designed to build virtual exhibition using VR technologies with ease.

Our focus in this paper is to present an app providing virtual navigation features on top of mobile devices, adopting an intermediate level of immersion. We provide a mobile access to hidden or inaccessible sites (e.g. caves, temples, buildings, etc.), using 3D representations and breaking the usability barrier that often hinders the navigation in complex models on top of mobile devices.

VirtualTour is a virtual navigation app for Apple iOS 7, 8, and 9 (tablets and smartphones) which supports the easy and natural exploration of CH sites captured with 3D scanning technologies or modeled by artists. VirtualTour proposes a novel approach for exploring virtual sites by exploiting modern mobile devices (tablets and phones) and their embedded sensors. The navigation is constrained to follow a predefined path in the virtual space; the user can move along on the path either by manipulating a simple slider or directly walking in real-world. The device sensors detect user's steps and progress accordingly in the virtual visit. The view is rotated according to mobile device's rotation, which is detected using the embedded device sensors.

VirtualTour includes two main subsystems: Viewer3D, a real-time rendering engine for 3D models, and RealMove, a navigation system which exploits the sensors embedded in mobile devices for driving the navigation interaction.

A. *Viewer3D*

Viewer3D is a software component that allows real-time visualization of 3D models on mobile devices (both phones and tablets), see Figure 2. The software is a framework developed for the Apple iOS platform and currently supports operating system versions from iOS 7 to iOS 9. This allows achieving compatibility across all iOS devices produced in the last 4 years, i.e. iPhone 4 and newer, and iPad 2 and newer.

Viewer3D is a rendering engine that relies on OpenGL|ES 2.0, a graphics library built specifically for mobile devices. This is the industry standard for creating high performance 3D applications on low power devices, and it is fully supported by all major devices manufacturers, including Apple. Viewer3D supports different file formats, including the PLY and OBJ formats. These are the de-facto standards for 3D scanned models and 3D modeling packages, so their support is crucial in our renderer. The software is also based on the VCG library [3], which is used for loading 3D models and for the optimization preprocessing needed for the visualization.

Viewer3D is highly optimized for maximizing the amount of data that can be visualized on mobile platforms. It supports visualization of 3D models composed of up to 3 million triangles at 60 frames per second. At the same time, the viewer supports a color attribute of the models that can be provided by either assigning one color for each model vertex, or by using texture maps (up to 16 Megapixel size) which can provide additional color de-

Fig. 2. Screenshots showing the rendering of the Sant'Angelo church with VirtualTour running on an Apple iPad Air 1.

tails for models that require high color resolution and have low geometry complexity.
Viewer3D also supports point cloud data, which are also quite common in CH applications.

This component is highly customizable, including several visualization parameters (e.g. lighting of a 3D scene can be computed in real-time or it can be precomputed and stored in the 3D model as a color attribute). It enables the visualization of scenes containing/defined by multiple 3D models. Furthermore, depending on the specific needs of the application, Viewer3D allows customizing the appearance of the 3D model. Other than the simple color of the visualized object/scene, additional attributes can be visualized using different color layers that can provide, for example, color coding of different sampled variables (e.g. light exposure, humidity, chemical concentration of substances, etc.).

B. RealMove

Supporting free navigation in a complex 3D space is quite challenging when sophisticated interaction devices are not available. Even more challenging when we have only a small screen and use a mobile instrument (where at least one hand is busy since it has to hold the device). Therefore, we need different GUI design and interaction approaches, alternative to the ones implemented for desktop applications.

One solution could be to reduce our capability of freely navigating the space, to simplify interaction and maximize easy of use. Thus, we can endorse a *constrained navigation* approach: if we can accept a predefined navigation path through our architecture, then reducing the degree of freedom in navigation has a positive impact in the management of the interface. VirtualTour endorses this approach: the user can navigate inside the virtual reconstruction along a predefined path, either walking forward or backwards. The use of a predefined path is not only justified by GUI-related reasons, but it can be also beneficial to guide the user to important areas of the virtual sites.

The speed along the path is controlled by the user. There are two mechanisms for controlling the speed: a slider rendered in view space (standard GUI interface) and directly

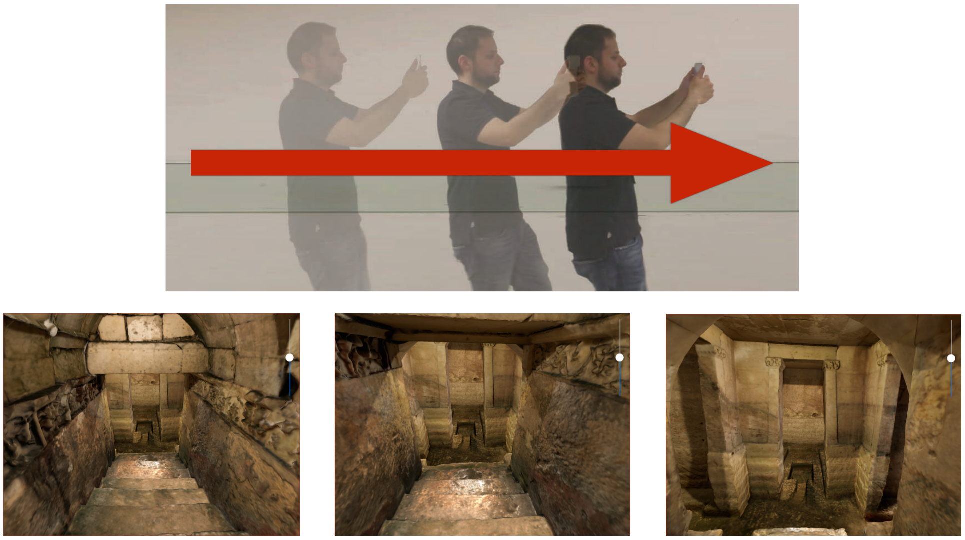

Fig. 3. RealMove component: while a user walks in the real-world space, we detect his steps using the device accelerometer; then, the movements of the user are transferred into the virtual world by advancing the virtual camera (images on the bottom).

by walking in the real-world (natural interface).

- **Speed slider**. This is a classic GUI slider (see the top-right corner of screenshots shown in Figure 2) which can be activated by a single finger, also while holding the tablet.
  Moving the slider upward means a constant forward speed (i.e. moving forward), moving the slider in the middle means zero speed (i.e. steady state, no movement), and moving it downward means a constant backward speed (i.e. moving backward).
- **Walking**. This mode allows driving the navigation by directly walking in the real-world, see Figure 3. We implemented a step-counter [4] by using the accelerometer sensor of the mobile device.

The above interaction modes allow driving the dynamic change of the view location. But what about the *view direction*? Conversely to view location (that is constrained on the predefined path), the selection of the view direction is left totally free. The user is totally free to look in any direction, following her/his personal interest and curiosity. This is implemented very easily by endorsing the *window-over-the-world* metaphor. Our mobile device is our window over the world, so to modify the view direction the user has simply to move the mobile device (her/his virtual window) to the requested direction of view. The interface is extremely natural: if we want to see what is slightly above the current view, we have only to move in that direction the tablet/phone. Therefore, we can rotate the device around our head to inspect the entire space around us.

IV. THE TEST CASES

We have tested the VirtualTour system on two CH sites (see Figure 4).

The first one is the rocky church of Sant'Angelo (Casalrotto, Taranto, Italy), a 11th-14th century church totally dug in the ground. This church is the only example in Italy of a two levels rocky church. Some details on the 3D digitization of this artwork have been already presented in Section ii.

The second one is the Palmieri hypogeum, a Messapian tomb built in the 4th century B.C., located in the city of Lecce (Italy). This burial vault is located below a garden in a private house; even if it is a masterpiece of that ancient civilization, it is not accessible to the public due to property and security issues. The 3D model of the Palmieri hypogeum was acquired by the Information Technology Lab of CNR-IBAM (led by Francesco Gabellone) using a time-of-flight scanner. A digital photographic campaign was also performed to acquire and mapping the color information of the tomb on the 3D model.

The limited accessibility of these two CH sites makes them two perfect case studies for VR exploration with the VirtualTour app.

V. CONCLUSIONS

This paper has presented VirtualTour, a virtual reality app for the Apple iOS platform, supporting the exploration of CH sites. The app exploits the embedded sensors of the mobile devices to transfer the real-world movements of the user into the virtual world. An empirical evaluation of the

Fig. 4. VirtualTour (running on Apple iPad Air 1) visualizing the Sant'Angelo rocky church (up) and the Palmieri hypogeum (bottom).

usability of our tool is ongoing.

Concerning future works, we would like to give the user more degree of freedom in the virtual environment without increasing the complexity of the GUI. This entails a more sophisticated use of the touch-based surface of the mobile device and possibly a more sophisticated management of the trackball. Another possible extension is to support the presentation of descriptive materials (e.g. short audio clips, images, and text) that could be associated to specific locations in space (i.e. hot spots); and they could be activated either by an explicit action of the user or by using a proximity criterion.

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