Tangible Interactions to Navigate Through Space and Time Inside a Virtual Environment

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Abstract. In order to present the results of their work to the general public, historians of science and technology represent technical systems, the activities associated to them and their temporal evolutions in Virtual Reality. The immersed user can then navigate spatially to observe the studied technical systems and temporally according to 2 time scales to observe the temporal evolution of these systems. The different concepts and scales of navigation make this task complex. We therefore propose a model for representing time in an activity model and a tangible user interface allowing a user to navigate spatially and temporally within a Virtual Environment.

Keywords: Tangible user interface · Virtual Reality · Cultural heritage

1 Introduction

Virtual Reality (VR) allows for immersive cultural mediation applications improving acceptability and learning [4]. In the context of history mediation, researchers can reconstruct past places in order to allow users to navigate between the different eras simulated. One of the main issue is to propose to the user an intuitive way to navigate in time in those environment.

In this context several techniques has been proposed. *TimeMachine Oulu* [13] is a mobile application for viewing reconstructions of the city of Oulu in Finland. This application uses a PDA to geolocate the user and display a graphical interface (Fig. 1(a)) showing a 2D representation of the city of Oulu and allowing the user to select the year he or she wishes to observe. In 2017, Koebel *et al.* propose *Biennale 4D* [10], a Virtual Environment (VE) representing the Swiss pavilion at the "Biennale di Venezia". This VE allows the user to access the archives of the different exhibitions that took place in the Swiss pavilion over time. The user can move spatially in the VE by teleporting and can navigate temporally by interacting with a virtual cube, each face of the cube representing a year (Fig. 1(b)). *Evoluson* [6] offers a VE to explore the history of Western music.

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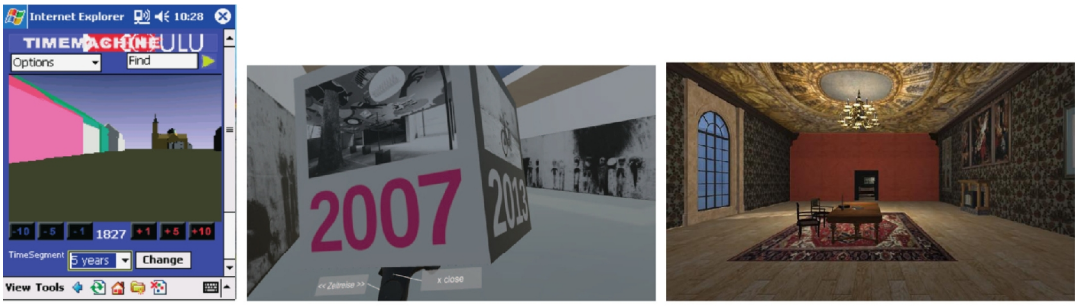
The user can listen to musical compositions based on Bach's "Art of the Fugue" in 8 eras from antiquity to the present day. Each era is represented by a room or a landscape and the user can change era by moving spatially (Fig. 1(c)). All these techniques are based on the fact that the number of periods to visit is limited and doesn't take into account hierarchy in the periods (century, years, days...). Their generalisation on complex navigation over time in virtual environments for cultural mediation aplication is not feasible.



(a) (b) (c)

Fig. 1. Left: graphical user interface of *TimeMachine Oulu*. Middle: virtual cube used to navigate temporally in *Biennale 4D*. Right: rennaissance era hall in *Evoluson*.

More precisely, in the domain of cultural heritage, History of Science and Technology (HST) studies technical systems and the activities associated with them. In order to test their hypotheses and present their work, historians use VR to reconstruct the systems studied and simulate technical activities. When immersed in a VE the user can navigate spatially to observe the technical systems, temporally in the short term to observe the effects of the activities on the environment and temporally in the long term to observe the effects of technological developments or historical events.

The multiple concepts and scales of navigation make the task complex for the user. Therefore, based on the theoretical benefits of tangible interfaces [8,9,14,17], we hypothesise that using a tangible interface would facilitate spatio-temporal navigation and improve the understanding of temporal evolutions of technical systems and activities represented in a VE. We derive 3 research questions from this hypothesis:

1. How to represent technical systems, activities and their temporal evolutions in VR?
2. Which interaction metaphors should we propose to allow a user to navigate spatially and temporally in VR?
3. Which tangible interactor should we use to support these interactions?

In this article we will first present our model of time representation in Sect. 2. We will then expose the functionalities we propose to navigate spatially and temporally in the Sect. 3. Finally, we will present our proposal for an interactor and the associated interaction situations in Sect. 4.

2 Spatio-Temporal Representation

In order to interact with the activities it is necessary to represent them. Several models propose to represent these activities and to execute them.

2.1 Temporal Representation in Activity Models

Activity models such as *CTTE* [12], *K-MADE* [3], *HAMSTER* [2] represent activities with a hierarchical architecture of actions. They base their representation of time on the use of *LOTOS* (Language of Temporal Ordering Specification) operators (e.g. parallelization of actions, choice between several actions etc.) and on the expression of the duration of an action. However, these models are only interested in the simulation of activities and do not allow the representation of technical systems involved.

However, other models allow the execution of activities in VE. *Mascaret* [15] is an extension of the UML meta-model for VR. This model allows technical systems and activities to be represented and simulated in VR. *Mascaret* describes activities, in the form of UML activity diagrams, as a hierarchical sequence of actions with associated resources. The flow of activities and their impact on technical systems is simulated and represented in the VE. However, *Mascaret* does not allow the representation and description of long-term evolutions due to technological evolutions or historical events. We therefore propose to add those concepts in *Mascaret* based on the works proposed next section.

2.2 Models of Temporal Representation in the History of Science and Technology

In order to describe and represent the results of their work, historians use ontology models. These models allow them to characterise periods of time according to criteria depending on their case of application.

PeriodO [16] is an ontology model whose objective is to simplify the indexing and listing of historical periods. A period is described as being composed of a temporal and a spatial extent. But *PeriodO* does not allow for the representation of activities, unlike *CIDOC-CRM* [5]. This ontology model was designed to facilitate exchanges between historians on cultural heritage by providing a common and extensible semantic framework. The temporal representation of *CIDOC-CRM* is based on 3 notions: periods, events and activities. Periods are sets of coherent phenomena or cultural manifestations linked in time and space. They are therefore defined by a temporal extent and a spatial extent. The combination of a temporal extent and a spatial extent constitutes a time-space volume. Events are changes in the state of cultural, social or physical systems. At a low level of detail events can be seen as having an instantaneous effect, but every process has a temporal and spatial extent. This implies that, at a finer level of detail, events can be considered as periods. Activities are intentional events conducted by actors leading to changes of state. Their difference from events is that they are intentional. Activities can be associated with a procedural document (e.g. a diagram or a plan). However, *CIDOC-CRM* does not allow for the description of the sequence of actions to carry out the activity.

ANY-Artefact [11] is an ontology model based on *CIDOC-CRM*, focused on the representation of industrial cultural landscapes [7]. *ANY-Artefact* represents time on two scales: a long-term scale represented by landscapes and a short-term scale represented by activities.

In order to represent the long-term evolution of technical systems and associated activities, we propose to use the notion of landscape and to align the temporal notions of *ANY-Artefact* and *Mascaret*.

2.3 Proposal for a Spatio-Temporal Representation Model for the Activities

In *Mascaret*, a system is described on two levels. The first level corresponds to the classes, grouped together in a model, allowing the structural aspect of the system to be represented. The second level corresponds to the concrete entities forming the system and instances of the classes declared in the model. These two levels are also used to describe the organisational structure and their instances. An organisational structure describes roles and resources which participate in the realisation of procedures. The organisational instances make it possible to assign the agents of the environment to the roles and the entities to the resources for an effective realisation of the procedures. An alignment between the notions of entities, organisational structures, roles and procedures and ANY-Artefact has been proposed in [1].

Mascaret represents procedures as a set of actions in the form of a UML activity diagram. However, it does not allow to represent the temporal evolutions on the long term of technical systems and procedures. We propose to integrate in *Mascaret* (Fig. 2) the notions of landscape, spatio-temporal volume and spatio-temporal event from ANY-Artefact.

A landscape (class *HumanActivityLandscape*) contains the semantic model (class *Model*) of the environment and the organisational structures (and thus the procedures), a set of spatio-temporal events (class *SpatioTemporalEvent*) and a spatio-temporal volume (class *SpatioTemporalVolume*). These volumes are composed of a temporal extent (class *TemporalScope*) delimited by 2 dates and a spatial extent (class *Area*) containing the entities of the model.

Let's take the example of a cultural mediation application dealing with the history of two bridges spanning a military arsenal and succeeding each other in time. Each of these bridges is emblematic of a specific landscape, so in this application we will study two landscapes, each corresponding to the duration of use of each bridge. Because the second bridge was built to replace the older one the 2 landscapes share the same spatial extent. Within these landscapes we find the two bridges as technical systems. The bridges spanning the military arsenal need to be able to open to allow ships to pass. This leads to an opening and closing procedure for each bridge. Therefore, in our application, we find 2

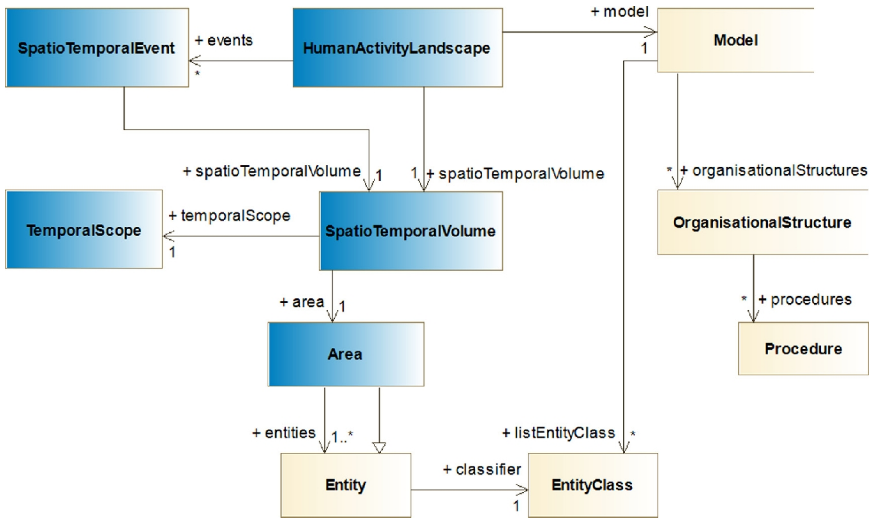


Fig. 2. Class diagram of our model. In blue the classes we integrate to *Mascaret*; in yellow the original structure of *Mascaret*. (Color figure online)

landscapes, each corresponding to a space-time volume. Each landscape includes 1 entity (the bridges) and 2 procedures.

This spatio-temporal representation model allows us to represent and interact with technical systems, the activities related to these systems and the temporal evolutions induced by technological changes or historical events. The following section presents the functionalities we implement to allow a user to navigate spatially and temporally within a VE.

3 Spatio-Temporal Navigation

3.1 Identification of the Functionalities

In order to identify the different functionalities necessary for spatio-temporal navigation, we organised a workshop with 12 experts (8 women and 4 men) in cultural mediation, history of science and technology and cultural heritage. On average the experts had 15 years ($SD = 8{\cdot}05$) of experience working on building cultural mediation scenarios or working with the general public. The objectives of this workshop were, firstly, to identify and define the user profiles likely to be concerned by spatio-temporal navigation in VR within a cultural mediation framework and then to identify the functionalities to implement in order to allow a user immersed in VR to navigate spatio-temporally.

These profiles then enabled us to write user stories allowing us to identify the spatio-temporal navigation functionalities. 69 stories were written by the experts, from which we drew 23 functionalities that we then grouped into 11 elementary functionalities (see Table 1). For example, the elementary functionality "navigate between different landscapes" can be done either by selecting a date or by selecting an event.

In these 11 functionalities, the first 7 are directly linked to spatio-temporal navigation, functionalities n°8 and 9 are not about navigation but allow to bring

Table 1. Summary of the 11 elementary functionalities

Id	Name	Features
F1	Change the speed of time flow	Speed up or slow down the speed of time flow in the VE to speed up the progress of a procedure or observe a step in more detail
F2	Navigate between different landscapes	Change the landscape shown in the VE to observe another place or time
F3	Navigate spatially within a fixed landscape	Change the viewpoint displayed in the VE to observe the technical systems represented
F4	Navigate in the course of a procedure	Select an action in order to observe the state of a system at an instant of a procedure
F5	Start the execution of a procedure	Start (or stop) the execution of a procedure in the VE
F6	Select landscapes	Select landscapes to navigate to later
F7	Select procedures	Select procedures to obtain information and initiate execution
F8	Access information relating to the selected landscape	Display information characterising the selected landscape (e.g. start and end dates, milestones...)
F9	Superimpose several temporal states	Display several landscapes at the same time in the VE (navigate in several landscapes simultaneously)
F10	Define time scales	Define or redefine the time scales used to perform activities or represent landscapes
F11	Create a landscape according to 2 dates	Create and add a new landscape in the application

additional information to the user. The functionalities n°10 and 11 are functionalities of control of the environment and instantiation of data, because they do not concern the spatio-temporal navigation or give the user access to informations, they are not essentials for our usecase.

This set of functionalities allows us to interact with the model in order to navigate spatially and temporally on 2 time scales. In order to achieve these functionalities we propose to design a tangible interface.

4 Interactions for Spatio-Temporal Navigation

The third step of our work consists in designing a tangible interface allowing a user to navigate spatio-temporally. To do this, we first organised an ideation and prototyping workshop. We then asked experts in cultural mediation to evaluate the proposals made during the workshop in order to determine which one to implement.

4.1 Ideation and Prototyping Workshop

The objective of our ideation and prototyping workshop was to design low-fidelity prototypes presenting tangible interactors and associated interactions.

The workshop lasted 4h30 and involved 16 participants (6 women and 10 men). Because our objective is to propose, design and build a tangible interactor for cultural mediation applications we invited people with competences in mechanical design, electronics and mediation. Among our participants we had researchers in computer science specialised in virtual reality and human-computer interaction, teachers in mechatronics and computer-aided design, historians of science and technology, cognitive psychologists, ergonomists and designers. These different profiles allowed us to obtain results focusing on different aspects of the design of an interactor. The participants were separated randomly into 2 groups and first took part in a brainstorming session around 2 questions: how to represent time in a tangible way? What kind of interactions to associate to each functionality? Following this brainstorming session, the participants took part in a design workshop, the objective of which was to propose tangible interactors taking up the elements discussed during the brainstorming session. The participants were given materials (paper, play dough, coloured crayons, Lego blocks) to design a low-fidelity prototype of their proposals and could work as they wanted, alone or in groups. 7 participants decided to work alone, 3 groups of 2 and 1 group of 3 were formed, either by affinity or because the participants proposed similar ideas. At the end of this session 11 low-fidelity prototypes and their respective interactions were proposed (Fig. 3).

Fig. 3. Examples of interactors prototype. Left: prototype n°1. Middle: prototype n°6. Right: prototype n°3.

4.2 Evaluation of the Proposed Interactors

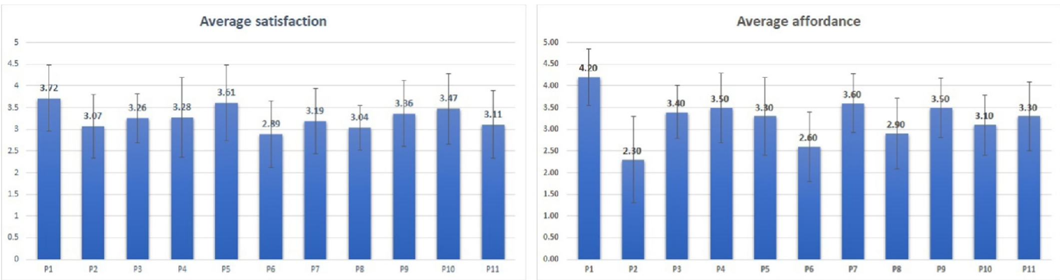
To evaluate the interactors proposed during the ideation and prototyping workshop, we asked 10 experts (5 women and 5 men) in cultural mediation to fill in a scoring table according to two criteria: usability and affordance. All of the participants had more than 5 years of experience in building cultural heritage applications or using them to show the results of their work.

The affordance criterion makes it possible to evaluate whether the shape of the interactor (i.e. the low-fidelity prototype) suggests its use. The usability criterion has been divided into 3 sub-criteria (ISO 9241-11 standard):

Effectiveness does the interactor enable the user to achieve his objective, to carry out the intended task?
Efficiency is the interactor easy to use, does it require much Effort to use?
Satisfaction is the interactor pleasant to use?

Each criterion and sub-criterion was evaluated on a scale from 1 to 5, with 1 being the worst and 5 the best. The affordance criterion was to be evaluated for the whole interactor and the usability sub-criteria were to be evaluated for each of the functionalities handled by the interactor.

Due to the health situation this evaluation was carried out remotely, we sent each participant a document explaining each feature, each interactor and each criterion. As a result, we were not able to make an objective measurement of the use of the prototypes, so we focus our analysis on the most subjective criteria, namely affordance and satisfaction.



(a) (b)

Fig. 4. Top: average satisfaction with 95% confidence interval. Bottom: average affordance with 95% confidence interval.

For the satisfaction criterion, we calculated the average satisfaction for each functionality and compared these results considering a 95% confidence interval (see Fig. 4(a)). The affordance criterion is the average of every experts evaluation (see Fig. 4(b)). We did not observe any significant difference between the prototypes, thus we cannot eliminate any prototype.

The expert evaluation did not allow us to designate an interactor with certainty. Therefore, we have also completed this evaluation by adding engineering criteria such as, for example, technical feasibility and manufacturing cost. The interactor that emerges from our evaluation as being the best compromise between affordance, user satisfaction and engineering criteria is the prototype n°4. It is an hourglass-shaped interactor (cf. Figure n°5(a)).

4.3 Implementing the Interactor

The interactor we decided to implement has the shape of an hourglass, 16 cm high and 12 cm in diameter (Fig. 5(b)). It is composed of 3 parts, an hourglass-shaped core and bases that can be changed according to the object tracking system used.

The interactor contains a Rapsberry Pi Zero board, a gyroscope, 12 inductive sensors (6 per side), 84 LEDs (72 in the core and 6 per side) and is powered by

Fig. 5. Left: low-fidelity prototype of our proposed interactor. Middle: 3D representation of our interactor. Right: implementation of our proposition.

an 11.1 V battery. The Rapsberry Pi Zero board allows communication with the computer, retrieving data from the sensors and controlling the LEDs.

The gyroscope is used to determine the tilt of the interactor and whether it is lying or standing. The inductive sensors are arranged in a circle under the bases of the interactor, they can be used as a circular slider or as a capacitive button. The driver we have developed differentiates the use of the slider and the button according to the number of sensors activated simultaneously. If the user wants to use the slider he will activate the sensors one by one, while to use the button he will activate several at the same time. We also propose to use the position and rotation of the interactor to interact with the system. By changing the bases we can adapt our interactor to the interaction scenario and the tracking system used.

4.4 Interaction Scenarios

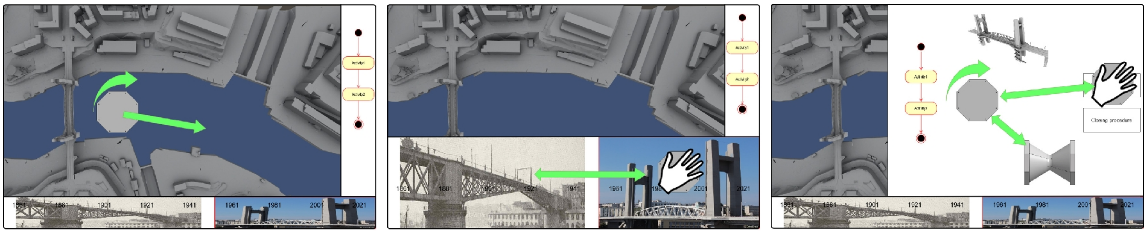
In order to verify the genericity of our interactor we deploy it in 2 configurations on a case of cultural mediation application around a technical system. The first configuration is based on a CAVE while the second one uses an Mixed Reality (MR) device.

In the first configuration the user is immersed in a VE through a CAVE-type system. Within this CAVE we place a white surface on which we place the interactor and project a graphical interface. The position of the interactor is tracked using the CAVE system.

The second configuration uses a see-through HMD to immerse the user. The use of a see-through HMD allows the user to see the virtual world and the real world at the same time and therefore be able to interact with the interactor while immersed in the VE. In this situation we replace the white surface with an interactive tangible interactive table. The graphical interface is displayed by this interactive table which is also used to track the position of the interactor.

The graphical interface is composed of 4 zones, each corresponding to 1 interaction mode. The user changes mode according to the task he/she wishes to perform. When an interaction mode is selected, the corresponding zone is spread out on the interface to occupy the major part of it. The other areas fold to their respective sides. To change modes, the user places the interactor on the folded area corresponding to the desired mode.

The first interaction mode is spatial navigation. The associated interaction zone is located in the middle of the graphical interface (Fig. 6(a)). The interface contains a top view of the VE. While in this mode the user can navigate spatially in the VE. His position in the VE is controlled by the position of the interactor on the interface. The rotation of the viewing angle is controlled by the rotation of the interactor on the support surface. To control the height of its position in the VE the user uses the circular slider on the top of the interactor (clockwise to move up, counter-clockwise to move down).



(a) (b) (c)

Fig. 6. Left: representation of our proposed interface with the interactor and the possible interactions in the spatial navigation mode. Middle: representation of our proposed interface with the interactor and the possible interactions in the temporal navigation between landscapes mode. Right: representation of our proposed interface with the interactor and the possible interactions in the temporal navigation on the procedures mode.

The second mode of interaction is the one for temporal navigation between landscapes. The corresponding interaction zone is located at the bottom of the graphical interface (Fig. 6(b)). This area contains a timeline representing the temporal sequence of landscapes. In this timeline each landscape is represented by a photo or an image. The user selects landscapes by placing the interactor on their representative image and validating their choice by using the capacitive button at the top of the interactor. When landscapes are selected they are displayed in the VE, thus the user can overlay multiple observed landscapes.

The third mode of interaction is the one of temporal navigation on procedures. The interaction zone displays the list of executable procedures and, when a procedure is selected, the flow and the 3D models of the resources of this procedure (Fig. 6(c)). To select a procedure, the user places the interactor on the element of the list of procedures that he wants, the choice is validated when the user removes the interactor from the list. To start or stop the execution of the selected procedure the user presses the button located on the top of the interactor. To navigate through the procedure step by step the user rotates the interactor on its vertical axis. The procedure navigation mode also allows the user to control the speed at which the time flows by using the circular slider on the top of the interactor. When used clockwise the speed of time increases, when used counter-clockwise the speed decreases. The tilt of the interactor also allows to control the speed of time flow, when it is vertical the speed is maximum and when it is horizontal the time is paused. Between these two positions, the evolution of the speed of time flow is linear.

The last interaction mode allows the exploration of iconographic resources resulting from the work of historians. In this interaction mode, the corresponding interface zone displays all the iconographic resources and documents enabling historians to define and describe the current landscapes. We do not implement this mode of interaction because it does not concern spatio-temporal navigation.

5 Conclusion

To allow a user to navigate spatially and temporally within a VE we propose a spatio-temporal representation model, a tangible interactor and a graphical interface. In order to evaluate the usability of our interface (interactor + GUI) we will carry out a comparative evaluation between our proposal and the use of a classical VR controller in the hardware configuration using a CAVE. This evaluation will take place in the context of a cultural mediation application for the general public. We will use the SUS questionnaire to measure perceived usability and will take objective measures such as task completion time.

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