4DIVE - A 4D INTERFACE FOR THE VISUALIZATION OF CONSTRUCTION PROCESSES IN A VIRTUAL ENVIRONMENT

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ABSTRACT: *In this paper we present 4DIVE, an interface concept for the visualization of construction processes in Virtual Reality (VR). It supports process management tasks of the AEC industry in the field of Virtual Design and Construction (VDC). 4DIVE is developed for the use in projection based Virtual Environments (VEs) like the CAVE or large scale projection walls, supporting stereoscopic visualization in real-time and 3D user tracking. The 4DIVE project focuses on the design of interaction concepts addressing the following topics: (1) The integration and visualization of 4D CAD models in VR systems, (2) the development of 4Record, a tool for recording and replaying paths in the 4D time-space, and (3) the design of suitable input devices and interaction techniques.*

KEYWORDS: *Virtual Reality, 3D User Interface Design, 4D Technology, 4D Building Models, Input Devices*

1. INTRODUCTION

4DIVE is a 3D user interface for process management tasks of the AEC industry using 4D models and Virtual Reality (VR) technology. It is developed to support decision making processes during the planning as well as during the construction phase. Therefore we currently develop a mobile Virtual Environment (VE), that allows to use 4DIVE directly at the construction site.

Within the project we keep the focus on the design of the 3D user interface, which takes into account, that up to now there are only few standards concerning dataflow, applications, input and output systems, interaction techniques and user interface design for VR. Therefore the 4DIVE project started with the development of an overall user interface design that includes the definition and development of the software but primarily takes care of a high ease of use of the whole environment.

In the 4DIVE concept the 4D CAD model of a building (while in this context time is the 4th dimension) is not only used for architectural visualization. It also serves as a 3D interface for the visualization of multi-dimensional processes representing the state of construction at a given time. Since all the information about the building will be

stored in a single Building Information Model (BIM), this allows the presentation of a variety of information for different stakeholders, e.g. for design or redesign purposes, for the simulation of alternative construction scenarios or for the controlling of ongoing processes. Thus, in a next step we will implement a connection to an external data base, which provides additional information of the building (or product).

2. 4D TECHNOLOGY

In the AEC industry 3D models are becoming well established for the representation and visualization of a project. However, 3D models do not efficiently represent and communicate other aspects of a project than geometry, especially not temporal ones. Consequently, they do not support project managers in the planning of schedules and in the testing of schedule alternatives. The extension to visual 4D models combines spatial and temporal aspects in order to display the progression of a project over time. In addition it becomes possible to present other information, e.g. used resources, prices, contractual information and the like.

4D models link components from 3D CAD models with construction activities, available resources, procurement restrictions and project schedules. The resulting 4D models allow project managers and other stakeholders to display the project development over time on a computer screen. Such 4D software has the ability to start and stop the timeline as well as to directly jump to any date requiring the attention of the user. Usually, additional information such as used resources or a status can be displayed as well. In this paper we address the topic of visualizing 4D models in Virtual Environments and we present appropriate interfaces supporting their visualization and manipulation.

4D models allow to review the planned status of a project in the context of a 3D model for any desired time. This allows project managers to check the integrity of the master schedule, reveals potential time-space conflicts and logistical problems, supports the communication of product and process knowledge and allows an efficient tracking of the work progress (Koo and Fischer 2000). Furthermore, 4D models facilitate the communication with sub-contractors and improve the collaboration between the project team. An overview over the current state of 3D/4D models in the AEC industry and how they support the construction processes is given by Hartmann and Fischer (2007). As 4D models tend to become quite massive in data to be tracked and held accurate, efforts have been undertaken to combine 3D CAD models with databases for the 4th dimensional data (Dawood et al. 2000). In 4Dive the 4D model is provided by the *Interactive Toolbox for 4D Modeling* (Märki et al. 2006), where the 3D data is stored in a VRML (Virtual Reality Modeling Language) file, and attached to a structure of construction information stored in three XML (Extensible Markup Language) files (see section 4.2).

In addition to these achievements, we explore possibilities to record paths in time-space. A part of this paper is therefore devoted to appropriate interfaces and interface concepts. However, we do not address the topic of how recorded time-space scenarios have to be arranged in order to give a lively and meaningful animation following a predefined storyboard. This will be the subject of a future paper. Here, we focus on technical and interface design aspects on how 4D models can be imported, viewed and manipulated in a VE.

3. INTERFACE DESIGN

As a concept, interface can be generally understood as meaning of the relation between human and artefact. Regardless of whether or not the artefact is an object that is physically present, such as a pair of scissors or a telephone, or immaterial information or structures of order, we always stand in relation to it. In this respect, interface describes the possibilities for utilization and action that emerge from and are established by the interaction between humans and artefacts. Bonsiepe (1996) describes it as the interdependency between a user, a task and a tool. A tool can be either a physically present or an immaterial artefact.

Because human experience and action cannot be standardized in the sense of a norm, interface design refuses to be reduced to the functional and formal/aesthetic design of user interfaces based on defined conditions and guidelines. Rather, relational structures are conceived through interface design, and these have a decisive influence on the handling of artefacts – something that must be taken into consideration in their development (Doulis 2004).

3.1 3D user interface design

This is especially true for interaction concepts in computer technology. They become more diverse. Supplementing traditional WIMP (windows, icons, menus, pointing device) interfaces, spatial interfaces with 3D trackers, 3D pointing devices and stereoscopic projection displays like a CAVE (Cruz-Neira et al. 1992) are becoming more widespread. Bowman et al. (2005) and Sherman and Craig (2002) give a good overview of the state of the art and future trends in this field.

For the design of these 3D interfaces, it is increasingly important that the aspect of spatial context is taken into consideration to a greater extent than currently done (Doulis 2004). Space is the basic system of relation for humans. It is probably the most important area of human experience. Humans orient themselves in and through space and its dimensions and they locate objects according to these dimensions. Space primarily describes the arrangement and volume of humans and material bodies. These "natural" characteristics of physical space provide an important basis for the design of 3D user interfaces and VR applications. According to Bowman et al. (2001) the main topics of 3D user interface design, next to visualization, are input and output devices, interaction techniques and system control. Eason (1991) recommended to include the socio-technical system into the design of user interfaces. His three level model shows which factors affect human-computer interaction (see FIG. 1). With *amalgamation* Doulis and Simon (2005) describe the interdependent connection between physical environment, input and output devices, interaction technique and virtual representation. This takes into account that different applications and technical setups need their specific interaction concepts.
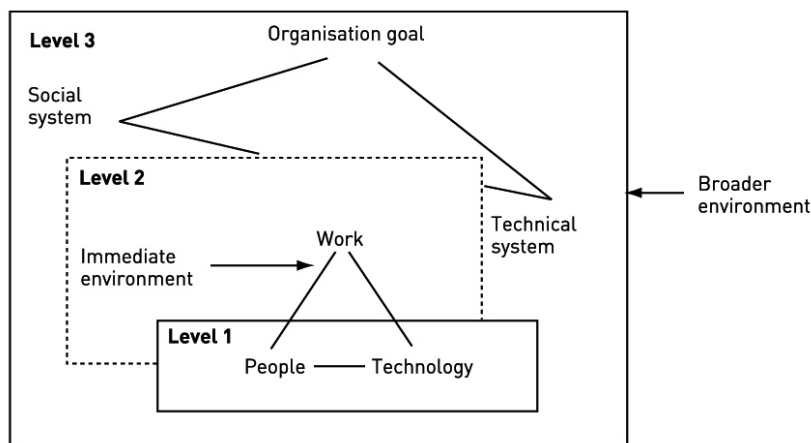

FIG. 1:   *3 levels of analysis for human-computer interaction (Eason 1991)*

3.2 The 4DIVE user interface

The 4DIVE user interface is part of the ongoing development of *iRoundTable*, a collaboration platform for large complex AEC projects with geographically dispersed interdisciplinary teams (Vogel et al. 2006). As a part of it, the *iRoomImmerse* concept includes the integration of Virtual Reality and Augmented Reality technology such as 3D tracking systems, stereoscopic displays and 3D sound, into common conferencing systems and applications.

Although VEs become more widespread, we have to take into account, that they are by no means a common part of the IT infrastructure used in AEC projects. People are not familiar with VR technology and they don't want to spend time on learning complex interfaces. On the other hand the spatial representation in natural scale provided by VR is predestined for the visualization of architecture and building processes. Therefore we decided to limit the functionality of the VR application to the interactive visualization of 4D models which lets the user explore the building process in 4D time-space and record this exploration (e.g. for preparing project meetings or documentation). This limitation of the VR software and the development of optimized interaction techniques and input devices increase the ease of use of 4DIVE and permit an appropriate integration in existing workflows of AEC organizations.

Although we think of the various components of a user interface as a single entity, our current development has focused on the following topics:

- The integration and visualization of 4D CAD models in VR systems (see section 4.2 and 4.3)

- The development of *4Record*, a tool for recording and replaying paths in the 4D time-space (see section 4.4)

- The design of suitable input devices and interaction techniques (see section 4.5)

The 4DIVE user interface can be divided into two parts. The first part concerns the visualization of the 4D model. This includes spatial navigation in the virtual scene as well as using the play function of the 4D recording application *4Record* (see section 4.4). 4DIVE uses VR properties like stereoscopic real-time imaging and 3D interaction (Kalawsky 1993) to increase the legibility of the presented 4D model. The user can walk through the presented 4D model like in real space. Additionally, he can use the interaction device for travelling in the virtual scene in a simple manner. Pressing the navigation button of the interaction device sets the starting point of the navigation. The user is able to travel through the 3D model by moving the device in the desired direction. The travel speed increases proportionally to the distance between the starting point and the actual position of the interaction device. Releasing the button immediately stops motion. This navigation technique is provided by the VR system and allows free movement in x, y, z direction. To prevent users from losing orientation in the virtual scene, only rotation along the yaw axis is enabled. With the play function of *4Record* the user can move forward and backward through the 4D time-space along recorded paths (see section 4.5.4).

The second part concerns the tool for recording paths in the 4D time-space. This allows users to record their navigation through the 4D model at a certain time. Both position of the user and schedule of the 4D model can be recorded (see section 4.4). To allow users to navigate through the virtual scene and to use the 4D recording application simultaneously, we developed one input device for each task. This clear separation keeps 4DIVE easy to use even for novice users (see section 4.5).

4. 4DIVE IMPLEMENTATION

4.1 Technical setup

4DIVE is optimized for the use with large scale stereoscopic projection displays. It was developed in the VR studio of the Academy of Art and Design FHNW with a stereoscopic wall/floor projection (280cm x 200cm) with 4 JVC Dila sx21 data-projectors with passive image-division for image separation, an A.R.T. optical IR tracking system with 4 cameras for user and device tracking (see FIG. 2) and in-house developed input devices. The installation is run by two HP 6200 graphics workstations. 4DIVE was developed on the VR framework Lightning (Blach et al. 1998) of the Fraunhofer Institute for Industrial Engineering IAO, Stuttgart.
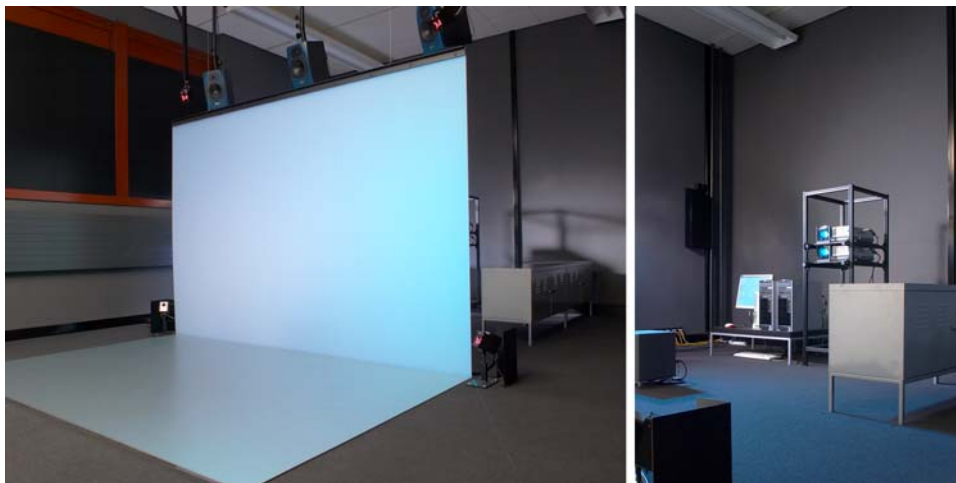

FIG. 2: *Technical setup of the VR studio*

4.2 Implementation of the 4D model in VR

In 4DIVE we present an animated 3D model of a building or a construction site, showing the daily progress of the building process. We can not only move spatially in the virtual construction site but also move in time through the whole building process from the beginning to the end, using the schedule of the activities included in the 4D model.

The 4D model contains 3D geometry data to which additional construction information is attached. This information contains a breakdown structure (BS) representing the construction order dependencies of the (3D) components and activities assigned to the elements of the BS and the resources required to perform them. Our 4D model is represented by four files; one VRML file containing the geometry information, and three XML files, one for the resources, one for the activities and one for the BS and geometrical components. Unique IDs are used to link the data in the VRML file with the data in the XML files.

We have developed a software called *Interactive Toolbox for 4D Modeling* (Märki et al. 2006), supporting the creation of such 4D models. The toolbox is also able to find an optimal schedule by using a genetic algorithm (Märki et al. 2006a). Internally it is using an object oriented database system. This system can store its information in XML files which allows consistency and serves as an interface to other applications. The 3D information is imported as an IFC (Industry Foundation Classes) or VRML file and can be exported as VRML.

The 3D model is shown stereoscopically and in real-time, allowing the user to navigate through the model and to watch it from different angles. Components of the 3D model are shown or hidden depending on the current time in the schedule, the colour of the material indicates the current status of the component in the building process. With the 4D player the user can move in time and see how the building develops.
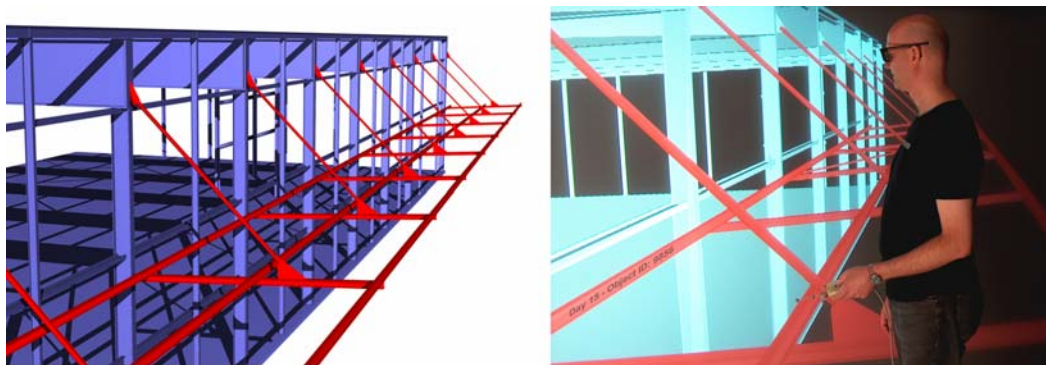

FIG. 3: *4D model of a building process, new components highlighted in red. (a) 3D CAD model; (b) VR model*

4.2.1 Concepts for data integration

We have evaluated two fundamental concepts for the data import into the VR system. In the first one, the VRML and the XML files of the 4D model are loaded directly into the VR system. This has the advantage of the VR system staying completely independent of any other software. The disadvantage is that an interactive change of the data requires a whole series of commands in order to update the model. Furthermore, as the data structure of the 4D model is constantly improved, it is more convenient to update the structure only once and not, as this concept would require, in both the *Interactive Toolbox for 4D Modeling* and the VR system.

The second concept provides a better solution in that only the 3D data is loaded in the VR system. The information about the state of a component, which is needed for the animation, is transmitted from the toolbox over a network. The same applies for the navigation commands of the user to control the VR model and the animation. With this concept we also do not have to implement an XML-Reader in the VR system. Although a separate application outside the VR application has to be run in parallel, changes in the 4D data only effect the toolbox but not the VR system. Thus, the VR system is only used as an input-output device.

4.2.2 Data flow

The network interface concept described above is implemented as a 4D controller. The dataflow diagram given in FIG. 4 shows how the 4D controller is linked to the VE. A more detailed description of the 4D controller and its network interface is given in the next section.
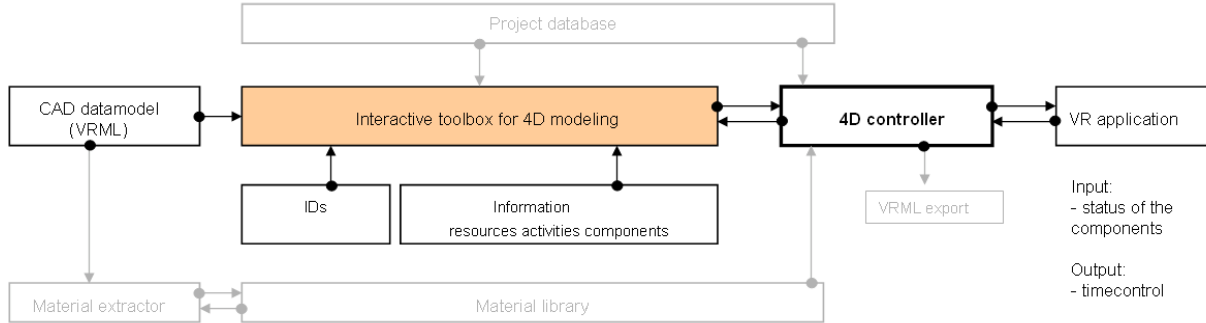

FIG. 4: *Dataflow diagram*

Starting with the export of the 3D model out of a CAD system, the data is loaded into the *Interactive Toolbox for 4D Modeling*, which semi-automatically creates and optimizes a 4D model. After the 4D model is created, the data is exported as a VRML file, containing the 3D model with additional IDs providing information about the (building) state of each component. The 4D controller then adds the material nodes and exports an additional VRML file, which is loaded by the VR system. It can be accessed and modified in the 4D controller.

4.3 4D controller

The 4D controller provides two plug-ins, one for the *Interactive Toolbox for 4D Modeling* and one for the VR system. These two plug-ins initialize a network connection, such that the Toolbox can use the VR system like an input and indicator (see FIG. 5).
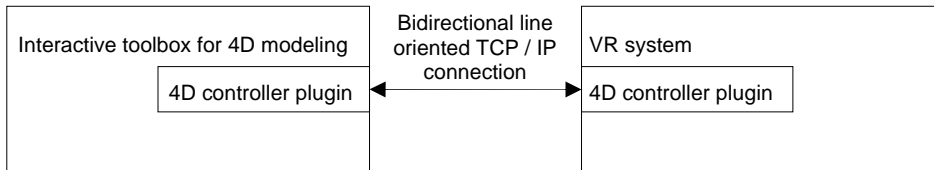

FIG. 5: *4D controller*

The communication works over a simple TCP / IP protocol, allowing the systems to run on separate computers. In order to minimize the transmitted data, only changes of the state will be sent to the interface. The 3D model and the materials are stored locally in the VR system and must not be transmitted.

On the other hand, the VR system notifies the toolbox when time steps are required. If the user steps in time, the VR system submits this information to the toolbox which returns the corresponding modifications of the components, materials and visibility states.

Command	Parameter 1	Description:
goto_start:		jump to the start of the sequence
goto_end:		jump to the end of the sequence
stop:		stop playing
start:		start playing

		pause
playdirection:	forward / backward	Notifies the Toolbox about the actual play direction.
speed_percentage:	Speed [0..1]	Sets the speed of the player. 1.0 means 100% which corresponds to one step (usual unit is day) equals one second.
set_time:	actual time	Sets the time of the player.
disconnect:		Disconnects the client from the server.

FIG. 6: *Transfer commands of the VR system to the toolbox*

An additional part of the 4D controller plug-in on the toolbox side is an extended exporter for VRML files. This exporter adds IDs to each component to uniquely identify them. When this VRML model is loaded into the VR system, the 4D controller can access the components by using the IDs and change the material and the visibility, depending on the building state.

For the transfer of the new states of the 4D model, the following commands have to be transmitted from the *Interactive Toolbox for 4D Modeling* to the VR system:

Command:	Parameter:	Description:
set_project_start_end_actual:	start time; end time; actual time	The parameters represent milliseconds since January 1, 1970, 00:00:00 GMT
stop:		stop playing
start:		start playing
pause:		pause
playdirection:	forward/backward	Notifies VR system about the actual play direction.
set_time:	actual time	The parameters represent milliseconds since January 1, 1970, 00:00:00 GMT
to_be_processed	name; type; process [0..1]; color	Submits the components, that are not yet processed.
start_processing	name; type; process [0..1]; color	Submits the components, that have started pro processing.
processing	name; type; process [0..1]; color	Submits the components, that are processing jet.
end_processing	name; type; process [0..1]; color	Submits the components, that stopped pro processing.
processed	name; type; process [0..1]; color	Submits the components, that have already been processed.

FIG. 7: *Transfer commands from the Toolbox to the VR system*

4.4 4Record

4.4.1 General function of 4Record

4Record, a component of 4DIVE, is an extension for recording and replaying navigation paths in a Virtual Environment. The path recording tool permits the recording of paths in the 4D time-space and saving them as

animations directly in the virtual scene. Once recorded, the paths can be replayed at any place in the virtual scene. This shortens the working sessions in the VE and also reduces the amount of information displayed.

Beside paths recording, the temporal sequences of the building process can be controlled. This allows the visualization of subsequent processes at a navigated place. After displaying the addressed temporal evolution, the navigation can be continued along the path in order to focus on the construction process at another place.

4Record provides the following functions for user interaction:
- Record
- Play, pause, stop
- Forward, backward, fast forward, fast backward, skip end, skip begin

4.4.2 Modes of 4Record

4Record differentiates between three modes:
- *Record mode* for recording paths and changes in the building process time
- *4D mode* for controlling the building sequence
- *Play mode* for playing the recorded path or playing the animation of the building process

Recording and replaying the path as well as the temporal sequence of the building process is controlled by a separate input device (see section 4.5).

Activating the *record mode* records the actual position, as well as the current sequence of the building process and the record time. By switching off the record mode it is possible to navigate back along the path and to continue the recording at a selected position or to navigate to another place and building sequence to continue the recording there. Therefore the path can be adjusted at any desired point in the 4D time-space. Quitting record mode automatically activates *play mode*.

The *4D mode* is for controlling the building sequence of the 4D model. By turning on the 4D mode (which causes switching to the control of the building sequence) with record mode still activated, the temporal sequence can be precisely controlled and recorded.

The replay function shows the recorded path with its building sequence. Similar to the functionality of a video recorder it is possible to seek within a recording stepwise forwards and backwards, as well as jump to the beginning or the end of the recording in an easy way. It is also possible to interrupt the replay at any time to navigate freely or to display different sequences of the building process. Afterwards, the recorded path can be continued.

4.4.3 Implementation

The application for recording and replaying is implemented as a TCL (Tool command language) script using a custom C++ plug-in for Lightning. It saves a vector of seven values for each frame: the position of the camera (three values x, y, z), the angle of the camera (yaw, pitch and roll) and the time in the building process (the single value proc) (see FIG. 8).

When playing the animation, the position and orientation of the camera and the time in the building process are set to the recorded values of the frames. Consequently, the velocity of the animation depends on the frame rate. If the animation is recorded at a higher frame rate than the replay, the animation will be slower.

A more advanced solution is to record these seven values "within the recording time", so that actually eight values are saved. By replaying the recorded animation, the frame time can be interpolated from the recorded frames. This allows replaying of recorded animations independent of the frame rate.
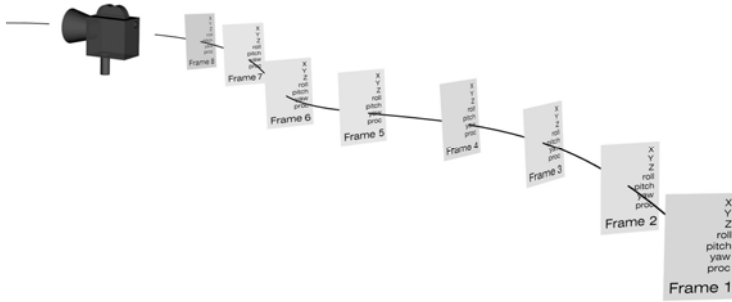
FIG. 8: *schematic view of path recording*

4.5 Input Devices

Because of the lack of a common interface or interaction standard for VR applications, we decided to develop two input devices optimized for the use in 4DIVE. One is used for basic 3D interaction, the second one is used for *4Record*.

In an early phase of the project, only one input device was used for both 3D interaction and the triggering of chronological events using *4Record*. Since the number of maloperations was significant, we decided to separate these tasks by using two input devices. This clear separation of *4Record* from the main functionality of the virtual scene by implementing it as a hardware device keeps 4DIVE clear and usable. The body of the input devices are slanted to provide an ergonomically correct handling.

The modular construction allows the use of the main body and technical components (e.g. radio transmission module and the controls) for both devices (see FIG. 10). All specific components (e.g. the target for the optical tracking) can be attached easily. Due to their symmetrical design, the devices are suitable for both left-handed and right-handed users.

4.5.1 3D Interaction Device

The first device allows main 3D interaction in the VE, like navigation, object selection and manipulation. It is equipped with a target for a 3D optical tracking systems, push buttons for explicit commands and a radio transmission module for wireless communication. Since the grip and the device controls allow different ways of use, this device could be used for many different applications and tasks.

FIG. 9: *Input device - 3D interaction device (left), recording device (right)*

In 4DIVE the input device is used in the following constellation:

- A target for the optical 3D tracking system. The Infrared (IR) camera tracking system delivers information about the position and orientation (6-DOF) of the input device in the Virtual Environment. Based on temporal changes of position the required navigation direction is derived - based on the distance to the origin-point the navigation-speed is inferred.

- Four push-buttons - three of them are used for activating the different modes: navigation, selection and manipulation; the fourth button, currently not in use, can be assigned freely.

- The middle push-button on the upper side of the input device activates the navigation mode, the left button is for the manipulation mode. The button on the underside of the input device changes to selection mode. This allows an easy selection of all functions of the device just with thumb and forefinger.

4.5.2 Design and construction of the 3D interaction device

The body of the input device consists of two parts which can be divided into handhold and operation area. An inclination of 16° between the operation area and the handhold guarantees an ergonomic use of the device. The handhold absorbs the forces of the thumb on top of the operation area and also fixes the components for wireless communication, energy supply (voltage and loading function) and a standard accumulator, which is used for the wireless transmission of push-button events to the VR system. The accumulator can be reloaded via a standard USB connection. This also enables a "cable-engaged"-operation if no spare accumulator should be available.

The 3D target for the optical tracking is attached in two holes on the front side of the device and is fixed with nuts in the internal of the body. Because the operation area is a separate part of the input device, it can be exchanged very
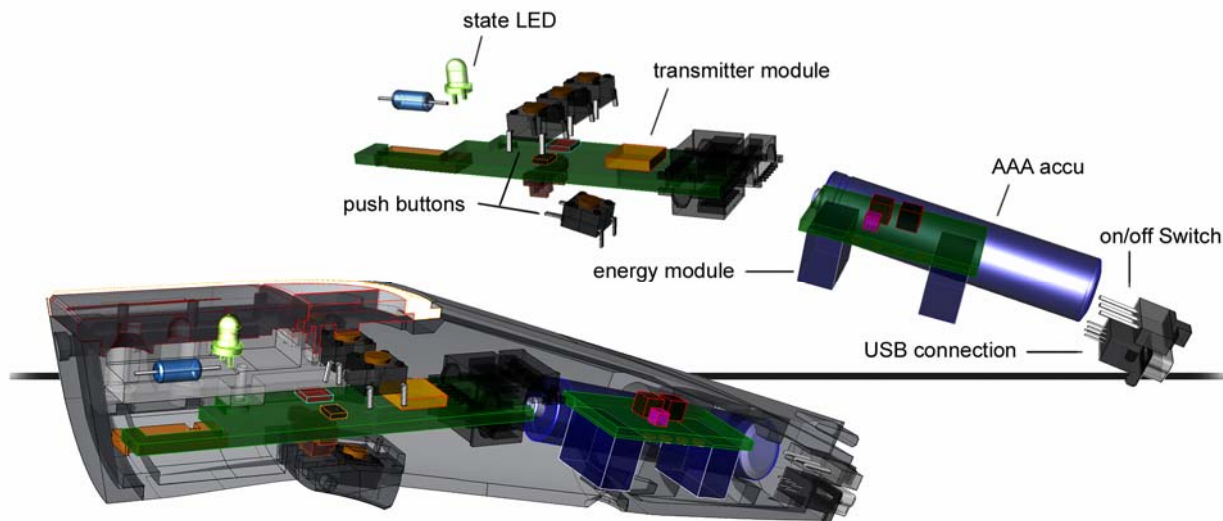
easily when other control components are used (see FIG. 9).

FIG. 10: *Technical components*

4.5.3 Recording device

The second device is the stand-alone recording device for *4Record*. Its interface is based on common portable devices like voice recorders or MP3-players. Thus even novice users will use the device automatically as intended and become quickly familiar with its functionality and its use.

The technical components like the radio transmission module, energy module etc. are the same as of the 3D interaction device. Three push buttons and a tact-switch as operation elements complement the equipment.

4.5.4 Usage of the recording device

We use the recording device to activate the basic functions during recording and replaying of navigation paths in VR and to play and control the current sequence of the building process. In *4Record* we differentiate between record mode, play mode and 4D mode. Furthermore we can move forward and backward in space along the path and the time corresponding to the building sequence. So we control the following functions:

- change mode (record / play / 4D)
- rewind, fast rewind, skip begin
- continue/pause
- forward, fast forward, skip end
- stop command to leave the record mode without any further action.

The main functions during the usage of the system are activated by the main control element - a "5-phase lever-and-push-operation-switch". The element has 2-phases in each direction as well as a centre push button and thus allows for navigation along the recorded path.

Three programmable push buttons are used for record, options (e.g. save or delete path) and for the change between the play/record mode and the 4D mode. If the record mode is selected the current position and the process-time is recorded. By pushing the record button (left button) again, the record mode is paused. If the record mode is stopped, the recorded path or the sequence of the building process – depending on the active mode – can be replayed. Two light-emitting diodes (LEDs) on the top side of the device give feedback about the current mode (see FIG. 11).

4.5.5 Design and construction of the recording device

The design of the recording device is similar to the design of the 3D interaction device (see FIG. 11). Since the position in space is unimportant for the recording device, an optical tracking target is not required. Also a button on the underside of the body is not used. A neck-strap attached to the rear area allows a comfortable and quick access. Nevertheless, essential differences arise in the construction of the operating surface (see FIG. 11).

FIG. 11: *Recording device*

5. CONCLUSION AND FUTURE WORK

With 4DIVE we present a VR interface to visualize construction processes. With respect to the demands of user interface design, we developed a concept to implement 4D models in a VR system. Based on VRML files of the 3D CAD data of a building, the user is able to record and replay paths in the 4D time-space using an application called *4Record*. Controlling main interaction and path animation tasks with only one input device is error-prone. We therefore developed a specific device for each task separately. Since the interface of the recording device is similarly designed as a voice recorder, users become quickly familiar with its use. This major design decision led to a significant reduction of operation errors and to a much easier use of the whole interface.

Keeping the focus on the design of the user interface, 4DIVE stands out due to its high ease of use, allowing the user to keep the focus on his task and shortening the duration of project meetings.

In a next step we will integrate external databases providing additional information about selected objects. The user will be able to select from different categories to display information like resources, time, etc. We will test both, displaying additional information in VR and on separate 2D displays. In addition, 4Record will be complemented with save and load functions in order to prepare different sessions using only one VR model.

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