A Small-scale, Low-budget Semi-immersive Virtual Environment for Scientific Visualization and Research

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Abstract

This paper describes the design concepts, the making of and some applications of the first Estonian Virtual Reality Environment. Using hardware only slightly above the threshold of consumer level, we built a virtual environment (VE) aimed at scientific visualization with the lowest possible space requirements (smaller than a cube with 2 m edge length in total) and budget (approximately below 30,000 €). The system is a fully functional visualization environment that replicates most of the features and properties of a real-sized CAVE-like System, therefore allowing further prototyping and research in the field of Virtual Reality.

Keywords: Virtual Reality; Stereoscopics; Estonia; Scientific visualization; Semi-Immersive; Magnetic Tracking

1. Introduction

1.1. Introduction to the Kyb3

The decision process that led to the Kyb3 (kju:b) project originated from two main reasons. The first one, specifically related to the research interests of the Institute of Cybernetics at Tallinn University of Technology (where the system has been built and by which it has been financed), was the need for a modern scientific visualization tool. The system has the dual aim of being a support for research and

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simulations, and to be used to display to non-scientists, in a visual and therefore more easily understandable way, the applications of the physical theories developed at the institute.

The second reason, more long-term but not less appealing, was to realize the first Virtual Reality project in Estonia. As this small Baltic country is currently reaching a European-wide fame for becoming the “Silicon valley of northern Europe” [1], our plan was to pioneer the research field of Virtual Reality with a low budget virtual environment (VE) that could be used to introduce researchers and industries to Virtual Reality concepts, to be eventually extended through a real sized CAVE™-like [2] system.

To achieve these aims, a small Virtual Reality system, able to reproduce most of the features available in room-sized CAVE™-like systems, was needed. The system should be designed in a way that, despite the constrained dimensions, it could easily illustrate the potential of such environments.

With the main (but not only) aim of the Kyb3 system to be applied to scientific visualization, it had to be powerful enough to manipulate large datasets but at the same time it had to be operated in a quite small room (approx. 3 x 5 meters), occupying no more than a 2 x 2 meter area and, being a prototype project, it had to be of limited costs.

The complete system, including frame, screens, projectors, mirrors, workstation and tracking system, has been built so that it can be assembled and disassembled relatively easily and transported in a small van or a large car. The total time necessary to assemble the Kyb3 (including projectors and mirrors alignment) is approximately 5 hours, while the overall weight does not exceed 150 kg.

The contributions of the Kyb3 are:

- Space and budget-constrained environment through an accurate use of short-throw projectors and mirrors and a single graphic workstation.
- Adoption of specific requirements for scientific visualization interaction.
- Opening the way to a completely new research field for Estonia representing a fully functional small scale prototype of a CAVE™-like System.
- Low-cost user tracking and interaction using Wintracker III magnetic tracker and Wiimote Plus.

1.2. CAVE™ Systems and small sized installations

Despite the initial euphoria that followed Cruz-Neira’s innovative concept in 1992 [2] the last decade witnessed a recession in the development of Virtual Reality Environments. The main reason was simply their high cost.

In spite of the availability of powerful low-cost hardware, a full-fledged full-sized VE can still reach costs that are unsustainable for small and medium sized research institutes, easily reaching several hundreds of thousands of euros, making it a definitely expensive research topic.

The high cost and the limited ongoing research consequently imposed also a strong constraint on the applications of VE in the private sector.

In its wider definition [3], a semi-immersive VE is a computer-generated environment mainly composed of interactive computer graphics, designed to physically and/or psychologically immerse one or more users in an alternative reality. A CAVE™-like system is a room-sized semi-immersive VE with the number of rear-projected bounding surfaces ranging from 3 to 6 (eventually including floor and ceiling). The user position inside the VE is tracked through an optical or magnetic-based system which enables the presentation of the correct perspectives and the correct stereoscopic effect.

Despite being visually impressive, the full sized CAVE-like systems have, as we mentioned before, two main problems: cost and size. We already spent some words on the price ranges that they can reach, but what about the needed space? With a traditional back-projection (mirror endowed), a typical prerequisite is to have at
least 3 meters of free space behind each screen (including floor and ceiling). This requirement, summed up with the size of the VE itself, usually enclosed in a $3 \times 3 \times 3$ meter cube, results in a huge space requirement of a cube with a 9 meter edge length for a 6-wall CAVE™-like system.

Several research projects have been dealing with space and cost limitations, examples of this are the miniCAVE at the Anhalt University of Applied Science in Köthen, Germany [4] and the PIT CAVE at the University of North Carolina at Chapel Hill [5]. Our approach, however, even if somehow inspired by those projects, presents several differences.

As we said in the introduction, we intended to realize a system for multiple users and demonstration of scientific visualization issues and we also wanted at the same time to implement on a smaller scale most of the features present in a room-sized CAVE™, to have a prototype on which to learn, and to be used to open the way to research in Estonia towards more complex virtual environments.

2. The Kyb3

2.1. Frame and screens

The Kyb3 Virtual Environment is composed by three rear-projection screens (two walls and one table screen), each one illuminated by a pair of short-range projectors driven by a multiple-GPU graphics workstation.

Due to the rectangular shape of the screens, and to eventually save additional space, one of the two wall screens, the one adjacent to the shorter edge of the table screen, has been slid back so that part of its surface (approx. 30 cm) will remain hidden (Fig. 1a). This will give a more compact external look to the system, and will moreover allow us to additionally support the screens from inside the frame.

The proper scene alignment using this particular frame positioning will be compensated through software configuration.

![Fig. 1 (a) Screens configuration concept (b) Screens configuration in the system (with mirroring) (c) Kyb3 Frame design](image)

The whole system is encased in a custom-made aluminium frame (built by OÜ Dimentio, Tallinn, Estonia) that supports the three screens and the movable parts that allow the positioning of the projectors and mirrors (Fig. 1b, 2b).

Additionally, the structure can be eventually disassembled to be moved. The whole structure is 1.90 m tall and 2 m x 1.70 m large, with the table floor suspended approximately 90 cm from the floor of the room (Fig. 1c). The height of the whole system has been chosen after several experimental setups (Fig. 2a) to allow a proper use of the table screen for above inspection of data, and so that the wall screens are taller than the average user height, therefore reducing the chance that the gaze of the user will float outside their boundaries, destroying the immersive feeling upon contact with the room. After multiple tests with different users, it has
been shown that the data is mostly kept in the corner between the three screens or on the lower part of the side screens.

The users tend to constantly look down with an angle that is approximately always between 30° and 45°, making therefore the chosen setup the ideal one.

The reason for the choice of aluminium versus steel as building material was related to the intention of using electromagnetic tracking sensors, and therefore the need to avoid the interferences caused by ferromagnetic materials [6]. Wood was ruled out due to its tendency to deform (wooden structures are considered to be sort-of “alive”).

For the screens we chose polymer-made acryl glass middle-grey polarization-preserving rigid back-projection ones of 92 x 122 cm of size.

2.2. Projectors and mirrors

We mentioned in Section 1 the need for a space-saving system and we have shown in section 2.1 the small size achieved by the system (a cuboid of dimensions 2 x 1.7 x 1.9 m). To achieve an image of the proper size (approx. 92 x 122 cm) with such a limited available space behind the screens (70 cm), two necessary requirements were short throw projectors and a mirror system.

After a long search we decided to use the Acer S5201B DLP projectors. With a 3000 lumen brightness and a 4500:1 contrast ratio on a 1024 x 768 resolution, they represented one the best compromises between quality and price of the systems available in Estonia, but what really made them the favourite ones was the extremely short throw range.

With a throw range of approximately 60 cm for an image of 100 cm of base, they were definitely the best option to achieve a large bright image while using as small space as possible. Using the online Acer calculator first, and performing some direct measurements afterwards, we obtained that the necessary distance to achieve the projection size we needed was approximately between 75 and 85 cm, but it had to take into account the need for applied keystoning to compensate the double projectors, and also the size of the projectors, whose length including cables is approximately 35 cm.

Summing it up with the necessary distance stated above, would have required a space behind the screens of approximately 120-140 cm, far too much for what we had available. From that, imperatively, arose the need to use mirrors to reduce that distance.

Through the use of short-range lenses and optical mirrors, the required image size is obtained with only 70 cm of space necessary behind each screen.
However, a very precise alignment of the projectors that uses the smallest possible amount of keystone effect was necessary for every screen due to the properties of short-ranged projectors, with which every fraction of degree of rotation, and every millimetre of relocation have an amplified strong effect on the image. This heavily influenced the design of the frame that we therefore designed and built with custom-made full movable mountings that allow the multi-directional configuration of each projector (as a pair and individually) and of the related mirror (Fig. 3a, 3b, 3c).

![Fig 3 (a) Projectors and mirror diagram (b) Projectors and mirror movable mountings project (c) Projectors and mirror mountings](image)

To complete the projector mounting, we built one small glass frame for each projector to hold the circular polarizing filters, for each pair of projectors the left eye filter and the right eye filter.

### 2.3. **Kyb3 Workstation**

While most of the real-sized CAVE-like systems run on a distributed network of multiple computers (usually at least one computer for every screen), this choice would have conflicted with our space and budget requirements and, as all the most commonly used VE software can also run on a single computer with multiple displays, we decided to choose this solution. The Kyb3 workstation has:

- Dual 8-Core Opteron 4284 3.0 GHz
- 64 Gb ECC Registered 1666 MHz RAM
- 4x Nvidia Quadro 4000 Graphic Cards
- Intel SSD 300 GB HDD

Three of the graphics card are used to drive the projectors (two projectors per card) while the fourth one is used for a control display external to the system.

While also a weaker computer might have been able to drive a demonstration system, scientific visualization, our main aim, has a very high demand for resources that a smaller machine would not support. The machine is furthermore equipped with an InfiniBand 40Gb card that will allow a direct high speed connection (40Gb/s) with the second graphic workstation in the same room (and that is used to control a Planar SD2220W 3D display). The Institute of Cybernetics new computer cluster can be accessed via 10Gb/s Ethernet for additional computational power. The operating system running on the graphic machines is Debian 7.1 “Wheezy”.
2.4. User tracking and interaction

One of the main prerequisites of a usable multi-screen semi-immersive system is the user interaction management. To maintain a correct perspective, a realistic stereoscopic 3D and to allow the user to properly interact with the scene, it is necessary to implement a reactive and precise system to track the position and orientation of the head and of the interaction devices in the three-dimensional space.

We analysed the advantages and disadvantages of the two main approaches (magnetic and optical tracking) and in the end, with both of them fitting our needs, we decided in favour of the electromagnetic tracking as our main user tracking system, buying a VR-Space Wintracker III device (Fig. 4a). The reason for this choice was first of all budget-related. Despite not being widely common, for a price of 1500€, limited compared to that of most of the other devices, the Wintracker III offered three tracked sensors with a high degree of precision (0.01 cm and 0.1°), with an output of approximately 90 values per second (divided among the number of sensors in use) and an effective range of up to 150 cm.

The drawback of working with a low cost almost unknown tracking device was that there were almost no documentation or user experiences available online about it, and there was no support software for testing under Linux. Also VRPN [7], our choice for input devices management, had no server class for the Wintracker III.

As a first step we therefore wrote a VRPN Server for the device (now part of the main VRPN trunk). Taking advantage of the fact that the Wintracker III is an HID (Human Interface Device), we encoded in the server not only the data reading and proper conversion into VRPN standards, but also the possibility of sending a list of HIDAPI library (http://www.signal11.us/oss/hidapi/) commands to the device when the VRPN server is started.

Through the configuration file it is therefore now possible to select how many and which sensors have to be activated, which hemisphere of the transmitter has to be used (the front one or the upper one) and if the optional range extender has to be activated or not. We installed one of the sensors on top of the polarized glasses, and we completed our first working head-tracking system (Fig. 4b).

As further progress, we introduced a Wiimote Plus wand as the main interaction tool, and we decided to adopt VRUI [8] as the main framework for applications and development. A first experimental attempt made with the Wiimote+ IR camera and a IR self-built LED beacon proved the IR tracking to be too limited in freedom for the size of our system and too unreliable. We therefore decided to couple the Wiimote controller with one of the Wintracker III sensors through a VRUI Device Daemon to provide the position and orientation (Fig. 4c). This combination proved to be an ideal low-cost interaction tool, due to the 11 buttons and a practical handle of the Wiimote and the precise tracking of the magnetic sensor.
3. Applications of the Kyb3

In Section 1.1 we mentioned that the Kyb3 VE has been built with the double goal of being employed as a scientific visualization tool and of being a development workbench for further research in Estonia about Virtual Reality and 3D Visualization. In this section we will narrow the focus on the two directions, giving some highlights on the applications fields on which the institute is working with the Kyb3, either as a tool or as an autonomous research subject.

3.1. Scientific visualization

The main multipurpose scientific visualization tool used since the beginning in the Kyb3 environment has been ParaView [9]. One of the main ongoing research directions in the Department of Mechanics and Applied Mathematics of the Institute of Cybernetics at TUT is related to micro-structured materials. One of the investigated materials is Steel Fibres Reinforced Concrete (SFRC) [10] [11]. The understanding of the influence of the orientation distribution of the fibres on the material properties is of crucial importance for safe usage of this construction material. 3D visualization is an important tool to achieve this goal.

Among the steps taken in the analysis was scanning cylinder samples of SFRC taken from full-scale floor slabs through a Computer Tomography. The volumetric data was filtered, segmented and skeletonized and afterwards the orientation of each object was analysed [10]. It was necessary to visually inspect the correctness of the analysis, especially of the correct separation of the touching fibres, for which a new algorithm had been developed. This inspection could not be performed on a 2D computer screen, due to the large number of thin objects. Therefore this was performed using stereoscopic visualization, using ParaView. In ParaView visual thresholding of the volumetric data has been performed, in order to isolate the fibres from the concrete and gravel in the 3D visualization (Fig. 5a).

![Fig. 5 Steel fibres reinforced concrete volumetric 3D Visualization](image)

While the visualization was possible with the Planar 3D Passive Polarized Monitor, there was still room for improvement.

We therefore chose ParaView, the only one among the software used in our lab being able to support a multi-screen tracked environment to visualize the fibres data on the Kyb3. Using our self written VRPN server for the head-tracking (Section 2.4) jointly with the VRUI Device Daemon for the Wiimote wand interaction (Section 2.4), we configured the interaction environment, while the screen positions and sizes could be configured directly from ParaView internal configuration files. The resulting level of visual understanding of the data was for all the test users much higher than the expectations. The size of the screens, joined with the 3D
depth perception and a natural way of interaction with the data (scaling, moving and rotation) given by the wand, fully satisfied the need of the user for a deeper interaction with the dataset. Here the system also proved its use to disseminate research results: the thresholded volume images have been shown to civil engineers, both from a university and a company, to demonstrate the problem of fibre alignment (or non-alignment). The possibility to “stick one’s head into the data” helped a lot in the explanation and understanding. Furthermore the visualization of fibre orientation distribution using tensor glyphs [12] [13] is under development. Ongoing research employs ParaView to visualize the simulation particle-laden flows performed with OpenFOAM. Of special interest are Computational Fluid Dynamics simulations of fibre distribution and alignment for different concrete casting methods.

In addition to the fibre-oriented visualization issues, several other software packages have been set up and are being investigated, to widen the range of scientific fields whose visualization might be managed through the Kyb3. VMD [14] has been installed and configured for molecule and molecular dynamics visualization; jReality [15] for mathematical surface visualization and a whole suite of software developed on VRUI for an even wider choice of datasets (e.g. LiDAR data, mesh objects, volumetric data).

3.2. Development

The second and more open-ended target was, as we said, the starting and pursuit of research focused on Virtual Reality techniques improvements and the development of software made and optimized to run on multiscreen VE. This research is currently branched in two different directions.

The first one, closely related to the scientific visualization issues described in Section 3.1, is aiming at the development of VE-based software able to fulfill some specific needs of the researchers at the Institute of Cybernetics. Employing OpenFOAM for the simulation of the flow of concrete together with the transport of cylindrical particles, we are currently designing and developing a visualization tool for VE, based on VRUI, for the visualization of the fluid flow together with the orientation distribution of the fibres by tensor glyphs. Therefore, the software under development will not only be dealing with the animated visualization of the CFD simulation, but also simultaneously extracting data from the simulations and performing a quantitative analysis on it, allowing therefore also the visualization of the tensor glyphs.

The second direction taken by our research team deals with developments related to VR itself, its techniques and methods and possible improvements. Currently, several topics have been proposed as BSc and MSc theses with the intent to create for the first time a generation of VR researchers in Estonia and to find students with an interest in the subject. The main development effort is being aimed towards the investigations on a low-cost and marker-free user-tracking system based on consumer-hardware, e.g., using multiple MS Kinect cameras.

4. Concluding remarks

With the Kyb3 we believe we have managed to obtain the results we were aiming for. That is, with a really low budget compared to the cost of traditional semi-immersive VE, we built a system that while fulfilling its own purpose as a scientific visualization tool, also allowed the Institute of Cybernetics at Tallinn University of Technology to start a complete new field of research, with several possibilities both as an autonomous or as a cross-disciplinary one.

The system, in addition to a really low price/performance ratio, has also been tailored to a very small space, obtainable only through a special self-made frame and the use of short-throw projectors and mirrors.

All in all the above mentioned results exactly fit with the objectives we established two years ago, and the first step of the creation of a 3D Scientific Visualization and Virtual Reality group is therefore complete, with the way now open for many more related further research topics.
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