The Responsive Workbench
A Virtual Work Environment for Scientists, Engineers, Physicians, and Architects

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Abstract

A virtual environment – the Responsive Workbench (RW) – was designed to support end users working on desks, workbenches, and tables as scientists, engineers, physicians, architects and designers with an adequate human-machine interface. We attempt to construct a task-driven interface for this class of users by working in an interdisciplinary team from the start.

The system is explained and evaluated using three applications – Medicine: education, a cardiological tutorial with a simulation system for ultrasound examinations of the heart, and surgery planning. Car industry: rapid prototyping for exterior and interior design and interactive visualization of flow field simulations (virtual windtunnel, combustion processes). Architecture: landscape planning and environmental research.

Virtual objects are located on a real "workbench". The objects, displayed as computer generated stereoscopic images are projected onto the surface of a table. The participants operate within a non-immersive virtual environment. A "guide" uses the virtual environment while several observers can watch events by using shutter glasses. Depending on the application, various input and output modules have been integrated, such as motion, gesture and voice recognition systems which characterize the general trend away from the classical multimedia desktop interface.

The RW is compared with other common virtual reality systems such as head mounted displays, BOOM systems and large screen displays. First experiences of the collaborators are analyzed, and future enhancements are proposed.

1 Motivation

The standard metaphor for human-computer interaction arose from the daily experience of a white-collar office worker. For the last 20 years desktop systems have been enhanced more and more, providing tools such as line and raster graphics, window-icon-mouse-pointer graphical user interfaces and advanced multimedia extensions. With the advent of immersive virtual environments the user finally arrived in a 3D space. Walkthrough experiences, manipulation of virtual objects, and meetings with synthesized collaborators have been proposed as special human-computer interfaces for the scientific visualization process. Specific human-computer interfaces, originally developed for pilots and telepresence tasks, became available to the ordinary user (see [4], [9], for example).

The dream of the ultimate medium, which uses all channels of human perception has guided the efforts of user interface design towards these virtual reality systems. Unfortunately, head-mounted displays, body-tracking suits, and force-feedback exosceletons are obstrusive. These systems separate the users from each other. Especially in scientific visualization applications, comprehensive attempts have been made to overcome these drawbacks. The BOOM (Binocular Omnidirectional Monitor) systems allow for easy-to-use walkthrough and object manipulation experiences [7]. The surround-screen projection-based virtual environment CAVE [5], [6] was designed for several users to become immersed with their whole body in a virtual space.

All these approaches to future user interface systems have one point in common: design of an (almost) universal user interface based on the most advanced computer and display technology available, with the implied requirement that all classes of users adapt to this artificial environment.

Another approach to the design problem for future human-computer interfaces is based on the early ideas of Myron Krueger's non-immersive, responsive multimedia environments [9]. This concept for a virtual environment rigorously centers the user's point of view. Application-oriented visualization environments have been proposed and built to support a specific problem-solving process. The computer acts as an intelligent server in the background providing necessary information across multi-sensory interaction channels (see [8], [10], [13], for example).

The computer with its connected sensors and reaction devices represents a responsive environment. For the design of a user-centered, task-driven responsive environment the following work in an interdisciplinary group should be untertaken:

- define a class of end users according to their major tasks,
- study their daily work environment,
- characterize their working behaviour, e.g., the use of specific tools,
- determine the role of cooperative work and the communication requirements,
- explore the incorporation of computer technology devices, such as workstations for use in simulation, visualization, and graphically supported access to data bases,
- identify additional requirements for future computing and I/O systems,

- estimate the importance of interactivity, capability of manipulation, and the use of multi-sensory interaction devices in parallel,
- describe the essential output modes of the task results and its storage and/or communication to other users, e.g., for non-sequential learning purposes,

We developed the Responsive Workbench concept as an alternative model to the multimedia and virtual reality systems of the past decade. Analyzing the daily working situation of such different computer users as scientists, architects, pilots, physicians, and professionals people in travel agencies and at ticket counters, we recognized that almost nobody wants simulations of their working worlds in a desktop environment. Generally, users want to focus on their tasks rather than on operating the computer. Future computer systems should use and adapt to the rich human living and working environments, becoming part of a responsive environment.

This paper describes the results of a joint attempt of computer scientists, engineers, architects, and physicians, to design a virtual environment — *The Responsive Workbench.* In the following we analyze the working environment and behaviour of this class of users, describe the general design of the RW system, and explain specific hardware and software tools we implemented. First experiences with applications are described and discussed. Finally further enhancements of the RW system and additional domains of its use, are proposed.

2 Analysis of User Tasks

The starting point for the project Responsive Workbenc was: We experimented with virtual reality systems such as HMDs (head mounted displays), data gloves, and a BOOM in applications like medical imaging, molecular design, fluid dynamics visualization, autonomous systems, and architecture. Many "computer friendly" specialists visited our lab. Basically, they had a positive attitude to the virtual reality technology, but recognized the shortcomings with respect to their needs immediately. Thus we decided to set up a new virtual environment based on the experiences with the "classic" VR technology. From the beginning we developed the concept for the Responsive Workbench in collaboration with engineers, architects, and physicians.

Comments of physicians during experiences with virtual reality systems such as head mounted displays, data gloves and the BOOM: The center of interest is the patient or the education process, not the operation of computer equipment. The typical working situations are cooperative tasks amongst specialists around a table with the patient on the table top, e.g., in surgery, radiation treatment, and medical education. Walking through a human head or the body of a pregnant woman with the aid of a HMD is certainly not an idea favored by physicians. The "virtual" patient should be seen as a whole body yet one should be able to zoom into an interesting substructure. The inclusion of "virtual" instruments would be very desirable. Generally, physicians are trained to visualize 3D configurations mentally, e.g., from x-ray or CT images, and to work with various analog and digital I/O devices in parallel.

Basic tasks of engineers and designers in car industry are: CAD tools, visualizations of simulations, and access to multimedia databases become more and more important to reduce costs and development time in the entire production process. Virtual environments are expected to revolutionize especially the design, manufacturing and maintenance tasks, where interactive and multisensory feedback plays an important role. Other applications will be marketing and driving simulations.

The architect's point of view: The ultimate design environment is and will be the designer's desk. Design is a process which is based on a dynamic, free floating interaction between brain, eyes, hands, and the environment. The basic requirements of a computer technology supported design workbench can be summarized as follows:

- Every action should be controlled exclusively by head movement, grasping and pointing with the hands, and the use of voice. No additional WIMP-like user interfaces should be incorporated.
- The design process should be interactive, starting from scetches with less detail to final "naturalistic" appearing versions.
- The virtual world should allow for interactive manipulation of position, shape, size, and material properties of the 3D objects.
- Object movement should refer to natural laws (gravity, collision).
- Observation of the architectural environment should be possible from arbitrary points of view, e.g., birds eye view, pedestrian view.
- The simulation of varying lighting conditions (sun vs. overcast sky, times of day) would be very helpful.
- Fast comparison with earlier and/or alternative model versions should be possible.

The next section describes the system we derived from this analysis.

3 System Description

During the analysis of the working environment and of the behavior of the specialists, we recognized that the (cooperative) tasks of this class of users relies on a "workbench" scenario. The future impact of desk-like user interfaces in general have been discussed in [12]. Using a beamer, a large mirror and a special glass plate as table top, we built an appropriate virtual environment.

Virtual objects and control tools are located on a real "workbench" (see Figure 1). The objects, displayed as computer generated stereoscopic images are projected onto the surface of the workbench. Depending on the application, various input and output modules can be integrated, such as motion, gesture and speech recognition systems. For example, in a teacher/student scenario a guide uses this virtual environment while several observers can watch events through their own stereo glasses (see Figure 2). Several guides can work together on similar but separate environments either locally or by using

Figure 1: Setup for a stereoscopic display of virtual objects on a desk

broadband communication networks. A responsive environment, consisting of powerful graphic workstations, tracking systems, cameras, projectors, and microphones, replaces the traditional multimedia desktop workstation.

Implementing the Responsive Workbench required close attention to several important elements: the user interface, feedback speed, and real-time rendering.

The most important and natural manipulation tool for virtual environments is the user's hand. Our environment depends on the real hand, not a computer-generated representation. The user wears a dataglove with a Polhemus sensor mounted on the back. Gesture recognition and collision detection algorithms, based on glove and Polhemus data, compute the user's interaction with the virtual world objects.

Another approach for interaction with virtual world objects – natural language – fits well into our responsive environment. The user issues commands like "zoom in", "rotate" or "transparency", which the system recognizes with a neural network running on a dedicated CPU or separate workstation.

To get correct stereoscopic rendering from any location around the workbench the system must keep track of the guide's eye positions. We realized this by mounting a Polhemus sensor on the side of the shutter glasses. It delivers position and orientation data for the head, allowing the system to calculate the position of each eye (see Figure 2). Additional collaborateurs also can see the stereoscopic images with slight distortions as long as they move closely to the guide's movement.

The RW is mostly configured from commercially available equipment and software such as an SGI ONYX graphic workstation, SGI Performer, GL library, shutter glasses, data

Figure 2: Cooperative work of a physician and a student

gloves and Polhemus sensors for head and hand tracking. The usage of these systems have been discussed by [4] and [6]. For the applications running on the RW we implemented additional tools such as:

- off-axis stereoscopic rendering,
- interpolation algorithms for tracker–data based on quaternions,
- adapted prediction filters for head and hand movement,
- voice and gesture recognition systems based on a neural network model,
- simulation of surgery equipment in virtual space using a stylus system,
- design of application dependent control buttons.

Similar to other applications in virtual environments (see [6], [4]) our first experiences are:

Low latency plays an important role in virtual environments. The head movement needs the fastest possible visual feedback, because incorrect perspective rendering strongly reduces the realistic appearance of virtual objects. Therefore, the latest available Polhemus data is read directly before the culling process starts, defining the new viewing frustra. Hand tracking and speech recognition are not as real time critical. A delay of two or three frames does not seem noticeable, compared to a delayed head movement response. Fast directional sound feedback coupled to collision detection software further enhances the perceived realism of the user interaction.

All our experiments showed that tactile feedback via the data glove is most desirable. As long as there is no appropriate data glove available we simulate the collision event between the hand and the displayed object by a specific sound and a coloration of the touched object (see Figure 4).

4 Applications

Based on current research projects in the field of computer graphics, human computer interfaces and visualization, the following applications have been embedded in this new type of environment following the suggestions of the involved end users.

Medical Applications

1. Nonsequential training
   This scenario is based on a real sized model of a patient. Figure 2 shows the model, called the transparent woman, in a teacher/student scenario. The patient's skin can become transparent, making the arrangement of the bones visible (see Figure 3). Now the surgeon or student can pick up a bone with the data glove and examine its joints, or take a closer look at the bone itself (Figure 4). In current educational settings students are used to looking at medical maps of the human body. Sometimes there is a plastic skeleton available to teach them human anatomy. The responsive workbench offers a new quality in this area: The virtual patient could be examined in any detail through the zoom operation. Covered parts could be set free by removing the obscuring bones or organs with the hand or by making them transparent. Especially important for the understanding of many processes inside the human body are their dynamic aspects. We implemented two primary cases: the spatially exact reconstruction of the beating heart and the blood flow inside the transparent heart.

2. Simulation system for ultrasound heart examinations
   This research project has been developed in close cooperation with the Centre for Pediatry of the University of Bonn, Department for Cardiology, Germany.

   Originally, the project was designed on a multimedia workstation. The prototypes provide a cardiological tutorial and a simulation system for ultrasound examinations of the heart.

   Recently we implemented the system on the Responsive Workbench to meet the requirements of the surgeons for a virtual environment. Detailed visualizations of the beating heart can be explored as interactive animations. The user can rotate the model in order to examine the structural and dynamic features of the heart. Different visualisation modes (i.e., transparent, with/without blood circulation) are available. The complex interior structures and dynamics of the heart, valves, and blood can thus be examined (see Figure 5).

   The next implementation step enables virtual ultrasound examinations of the heart. The physician can simulate sweeps and rotations of the transducer for the diagnosis

Figure 3: The virtual patient with semi-transparent skin

Figure 4: Picking up a bone with the dataglove

Figure 5: Examination of the heart

of congenital heart diseases. Interior and exterior views of the beating heart model provide continuous visual feedback. The free positioning and rotating of a stylus as 3D input device simulates the handling of a transducer head. The corresponding ultrasound images will be displayed on a virtual 3D control monitor.

3. Surgery planning
   Real datasets, obtained from computed tomography (CT) or magnetic resonance imaging (MRI) measurements are visualized using isosurface techniques. Thus we get surfaces of constant density such as bones or the skin (Figure 6), but we loose fine details like blood vessels and soft tissue. Therefore we are implementing a direct volume rendering algorithm using the 3D texture mapping capability of the SGI Onyx workstation. In this way we will achieve a semitransparent rendering of tissues combined with shaded isosurfaces.

First discussion results during cooperative work with physicians are: Most important seems to be the incorporation of a haptic feedback system mounted on the glove. Tactile sensations are essential in surgery and pathology applications to provide the feeling of skin, soft tissue, and bones, for example. Force feedback appears to be very important in surgery simulations, e. g. in endoscopy. Also the use of a (stereo) sound system to simulate specific noises, would create an interesting feedback channel. Future applications under consideration are:

- online incorporation of stereoscopic images from volume visualization of CT, MRI and PET data;

Figure 6: Reconstruction from MRI measurements.

- stereoscopic visualization of high resolution data from confocal microscopy, e. g. cell interiors or nerve cell complexes;
- incorporation of stereoscopic video images from endoscopy to simulate minimally invasive surgery;
- simulation of laser surgery of the human eye;
- visualization of dynamic processes such as blood flow in the brain, lungs, and legs, or pulses of the nervous system.

The advantage of the RW system for physicians is the intuitive access to the virtual world. Additional experiments with multimedia workstations, stereoscopic display on large screens, and head mounted displays have proven to be less favorable due to the creation of "artificial" working situations, and / or drawbacks such as low resolution images and lack of interactive manipulation capabilities.

Applications in the car industry

In cooperation with scientists and engineers of the research department of Daimler Benz AG, Stuttgart, we implemented two applications concerned with fluid dynamic simulations on supercomputers.

After the first experiments in this application domain we expect that future virtual environments such as the RW will have a large impact on design and manufacturing.

General objectives are:

- reducing costs by virtual prototyping;
- saving of time in engineering analysis through the visualization of simulation results with the prototypes, e. g. air flow around the car, combustion processes, crash tests;
- interactive modification of design and visualization of immediate effects, e. g. of the car's interior;
- understanding of complex , spatial environments;
- testbed for maintenance tasks;
- support for remote cooperative engineering and designs teams.

1. The virtual windtunnel
   This application realizes the virtual windtunnel scenario [3] in the Responsive Workbench setting. The simulation data is taken from a finite element program running on a supercomputer or a highend workstation. In the first step we resample the data points from the finite element mesh to a regular grid to speed up particle tracing. Another possibility we are exploring is to do the particle tracing directly on finite element meshes to achieve more accuracy. This is clearly more computationally demanding, so it might restrict the number of particles, which could be handled simultaneously even if we create a separate process on a dedicated CPU for this purpose. The geometry data is also extracted from the finite element data and somewhat polished by a modeling system, e. g. by adding textures and so on.

   After these preprocessing steps the designer or engineer is able to look at the car in the typical prototype size 1:4. Some precomputed streamlines are added as an overview of the flow field. The stylus now serves as a particle injector to examine any area around the car in greater detail. The particle generation rate and their lifetimes are adjustable. The velocity values of the flowfield are globally scalable even if this is physically not realistic.

2. Combustion process

   The supercomputer simulation of the dynamics of the combustion process are visualized with the aid of test particles as rendering primitives (Figure 8). The essential physical properties to be visualized are the velocity field, pressure, and temperature. The combustion process is time dependent, so the data rate is much higher. The visualization shows the gas particle flow with temperature color coded during the injection process. These particle paths are precomputed during the finite element simulation, because the mass of gas particles cannot be neglected. Current implementation focusses on the interactive realtime exploration of the temperature and pressure distribution inside the cylinder with arbitrary cutting planes. The cutting plane is attached to the stylus which allows easy positioning. The finite element data is again converted to a regular grid, which is then used as a 3D texture in the SGI Onyx rendering system.

Figure 7: Virtual windtunnel scenario.

Figure 8: Combustion process

Basic requirements of the virtual environment in this application domain are a high resolution color display (at least 1280*1024 pixels) and the capability for realtime rendering of complex objects with non–trivial reflection and texture properties. The advantage of the RW system as a non-immersive virtual environment compared to the BOOM system are the cooperative work setting and the incorporation of multi-sensory interaction models.

Architecture and design applications

For the design and discussion process in architecture, landscape and environmental planning we implemented a basic testbed so far:

An architectural model is shown on the workbench, in our case the area around the buildings of our research institute (see Figure 9). In front of the table two architects discuss the model, moving around buildings or other objects, such as trees in the virtual world. Additionally lightsources can be set by the data glove to simulate different times of the day. For this environment the concept of active objects appears to be essential, e.g., cars driving around, pedestrians walking along the street. Objects such as trees can be added and translocated. The problem of generating an animation path for each object is easily solved by an additional Polhemus, which can be moved around in the virtual world like an object to be animated. The Polhemus generates the position, orientation and velocity data for the animation path.

Figure 9: Architectural planning scenario

5 Future Applications and System Extensions

Immediately, during the discussion of the RW concept, the set up of the whole system, and the realization of the first application scenarios, we came up with the following ideas for improvements and extensions:

- enhancement of I/O and rendering tools for the RW system;
- inclusion of other applications, suited to this specific environment;
- design of appropriate responsive environments for other classes of end users.

The RW system shares the basic problems with all virtual environments such as: real-time high-res rendering of stereoscopic images with realistic appearances for complex scenes; low latency with respect to the multi-sensory I/O devices; parallel management of rendering, tracking, and the speech recognition system, running as separate CPU jobs or even on separate machines; effective generation of large object samples within a hierarchical ordering; and appropriate system tuning to allow cooperative work for other local users and/or users on remote RW systems linked via broadband networks.

The RW system is designed to demonstrate the ideas and power of future cooperative responsive environments. Further applications under consideration running on this virtual workbench will be the simulation of air and ground traffic on airports, a training environment for complicated mechanical tasks, e.g., taking apart a machine for repair, landscape design and environmental studies via terrain modeling, and physically based modeling of virtual objects ("virtual clay"). These applications also rely on the workbench metaphor, but require specific interaction and I/O tools.

Other classes of end users are given by travel agencies, ticket counters on railway stations or airports, car driving simulators, or extended multimedia lecture rooms, for instance. These application domains may require similar rendering interaction and I/O tools, but completely different responsive environments have to be designed. We expect the construction of a large variety of adapted human-machine interfaces in the near future.

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References

[1] Adam J, *'Medical Electronics'* IEEE Spectrum, Jan. 1994, 70–73.

[2] Bajura M, Fuchs H, Ohbuchi R, *Merging virtual objects with the real world: Seeing ultrasound images within the patient*, Computer Graphics, July 1992, 203–210.

[3] Bryson S, Levit C, *'The Virtual Windtunnel'*, IEEE CG&A '93, July 1992, 128–137.

[4] Bryson S, Feiner S, *'Virtual Reality for Visualization'*, IEEE Conf. Visualization '93, tutorial notes #1, San Jose, 1993.

[5] Cruz–Neira C, Saudi D J, De Fanti T A, *Surround–Screen Projection–based Virtual Reality: The Design and Implementation of the CAVE* Computer Graphics, July 1993, 135–142.

[6] De Fanti T A, Saudi D J, Cruz–Neira C, *'A Room with a View'* IEEE Spectrum, Oct. 1993, 30–33.

[7] Dowall I E, Bolas M, Pieper S, Fisher, Humphries J, *Implementation and Integration of a Counterbalanced CRT–based Stereoscopic Display for Interactive Viewpoint Control in Virtual Environment Applications*, Proc. SPIE 1256.

[8] Green M, Jacob R, *SIGGRAPH'90 Workshop Report: Software Architectures and Metaphors for Non-WIMP User Interfaces*, Computer Graphics, July 1991, 229–235.

[9] Krueger M, *'Artificial Reality II'* Addison–Wesley, Reading, Massachusetts, 1991.

[10] Marcus A, *Human Communications Issues in Advanced UI's*, Communication of the ACM 36, No. 4 (April 1993), 101–109.

[11] Merril J R, *Surgery on the Cutting Edge – Virtual Reality Applications in Medical Education*, Virtual Reality World, Nov./Dec. 1993, 34–38.

[12] Newman W, Wellner P, *A Desk Supported Computer-based Interacting with Paper Documents*, Proc. of ACM SIGCHI, May 1992, 587–592.

[13] Nielson J, *'Noncommand User Interfacer'*, in: Communications of the ACM 36, No. 4, (April 1993), 82–99.

[14] Tendick F, Jennings R W, Tarp G, Stark L, *'Sensing and Manipulation Problems in Endoscopic surgery: Experiment, Analysis and Observation'*, Presence 2, No. 1, (1993), 66–81.