The Responsive Workbench

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Abstract

The Responsive Workbench (RW) is designed to support end users as scientists, engineers, physicians, and architects working on desks, workbenches, and tables with an adequate human-machine interface. We construct a specific interface for this class of users by working in an interdisciplinary team from the start.

The system is explained and evaluated in several applications: A cardiological tutorial with a simulation system for ultrasound examinations of the heart gives an example for medical education. The car industry may benefit from areas like rapid prototyping for exterior and interior design and interactive visualization of flow field simulations (virtual windtunnel, mixing processes), which are shown. Further ideas gives a demonstration project for architects.

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 (Binocular Omnidirectional Monitor) systems, the CAVE (Cave Automatic Virtual Environment), and enhancements and extensions. First experiences of the collaborators are analyzed, and future enhancements are proposed.

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Additional Keywords and Phrases: Computer Graphics, Virtual Reality, interface, scientific visualization, stereoscopic, rendering, medicine, architecture, demonstration interfaces, direct manipulation, human-computer interaction, interactive, 3D graphic display, information visualization, responsive environments

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, WIMP(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 interfaces, originally developed for pilots and telepresence tasks, became available to the ordinary user (see [6], 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 exoskeletons 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 systems allow for easy-to-use walkthrough and object manipulation experiences [3]. The surround-screen projection-based virtual environment CAVE [2] 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 interface based on the most advanced computer and display technology available.

Another approach to the design problem for future human-computer interfaces is rigorously centered on the users's point of view. Myron Krueger pioneered this attempt with his work on non-immersive responsive environments [6]. 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 [4], [8], 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 undertaken (see also [5]):

- 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 their processing (storage 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 professional people in travel agencies and at ticket counters, we recognized that there is almost only small acceptance of a simulation of 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 different 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.

2 Analysis of User Tasks

The starting point for the project Responsive Workbench was: We experimented with virtual reality systems such as HMDs (head mounted displays), glove devices, 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 develope a virtual environment adapted to one specific class of users. We analyze the working environment and behaviour of physicians, engineers, and architects.

Comments of physicians during experiences with virtual reality systems such as head mounted displays, glove devices, 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 computed tomography (CT) images into an organ of interest, 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 architects' point of view: The ultimate design environment is and will be the designer's desk. The basic reqirements on an architectural workbench supported by advanced computer technology can be:

- 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 sketches 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.

3 System Description

During the analysis of the working environment and of the behaviour 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 has been discussed in [7]. 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. The projection parameters are tuned such that the virtual objects appear to be above the table. The maximal height is about 40 cm limited by the size of the desk. 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 broadband communication networks. A responsive environment, consisting of powerful graphics 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.

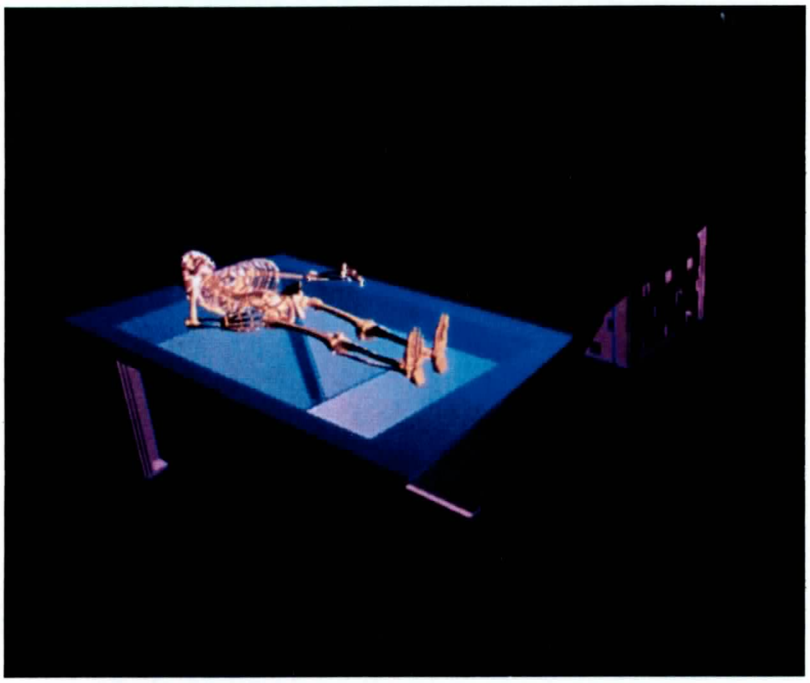

Figure 1: Set-up for a stereoscopic display of virtual objects on a desk

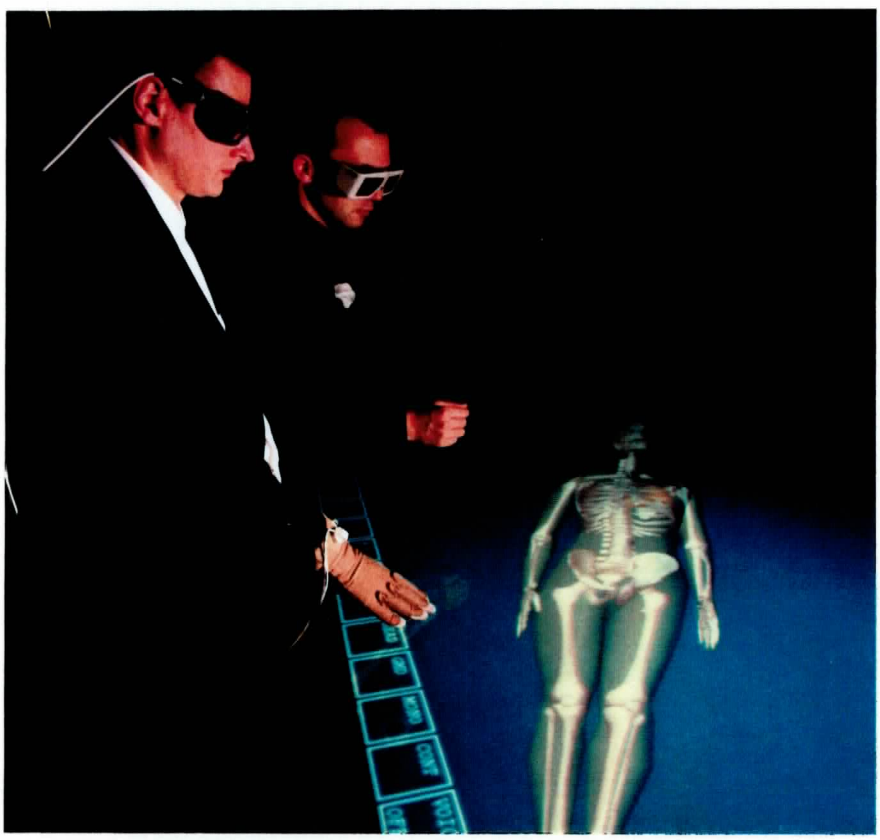

Figure 2: Cooperative work of a physician and a student

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 glove device 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 — 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(SiliconGraphics) Onyx graphics workstation, SGI-Performer, SGI-GraphicsLibrary(GL), shutter glasses (CrystalEyes), glove device (CyberGlove), and Polhemus sensors (FastTrak) for head and hand tracking. 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 an artificial neural network,
- 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 [2, 3, 6]) 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. Hand tracking and speech recognition may be acceptable with a small delay of two or three frames. 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 glove device 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). Virtual reality specialists, end users and laymen liked to interact with the application examples during demonstrations, especially with the human body and the virtual windtunnel. Immediately they tried to grasp the virtual objects and to play with the given manipulation tools. The "natural" setting and the capability to share the experience with other users was highly appreciated. The distortion of the objects due to the single-user perspective rendering was considered to be most disturbing.

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 glove device 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.

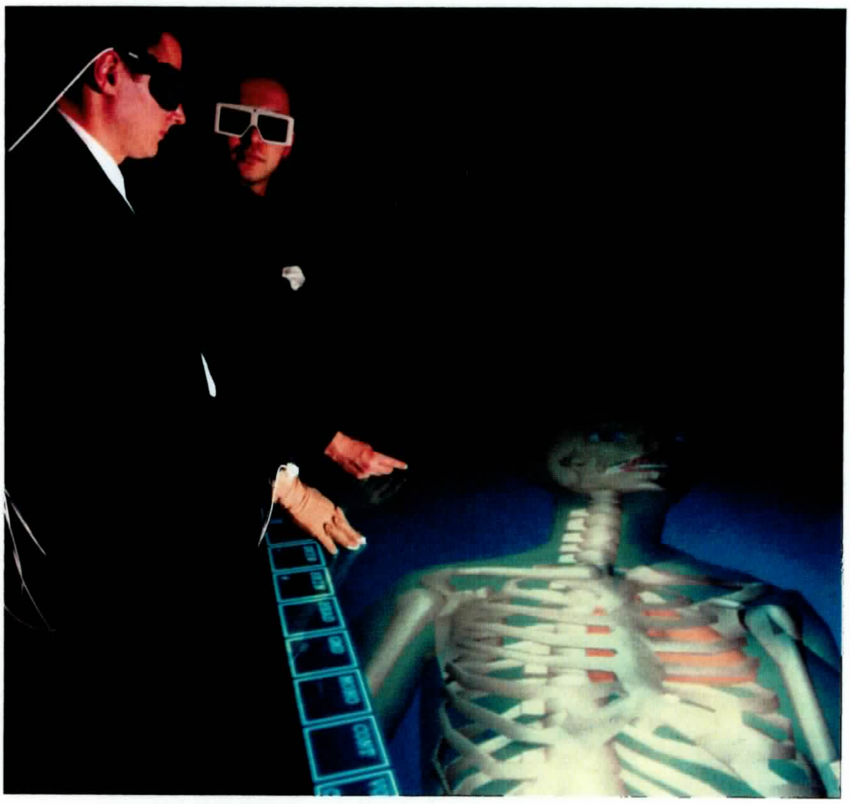

Figure 3: The virtual patient with semi-transparent skin

Figure 4: Picking up a bone with the glove device

2. Simulation system for ultrasound heart examinations
   This research project has been developed in close cooperation with the Center for Pediatry of the University of Bonn, Department for Cardiology, Germany. A typical user team is made from a radiologist, a surgeon and a visualization specialist.

   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. They want to see the organ of interest and the measurement process in real or magnified size from all points of view in 3D space. They also would like to compare the simulation with the images on TV screens originating from the scanning process. The model of the body should correspond to that of the patient. The entire virtual environment should be designed as close as possible to their natural working 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 visualization 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 5: Examination of the blood flow in a human 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 a 3D input device simulates the handling of a transducer head. The corresponding ultrasound images will be displayed on a virtual 3D control monitor.

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 device. 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, Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET) data,
- 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.
General objectives in design and manufacturing 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, mixing 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 design teams.

1. Virtual windtunnel (see Figure 6)
   This application realizes the virtual windtunnel scenario [1] 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 in exploration is to do the particle tracing directly on finite element meshes to achieve more accuracy, allthough the additional computational costs restrict the number of particles, which could be handled simultaneously. The geometry data is also extracted from the finite element data and somewhat polished by a modeling system, e.g. by adding textures. Some precomputed streamlines are added as an overview of the flow field.

   The stylus serves as a particle injector to examine any area around the car in 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. Mixing process
   The supercomputer simulation of the dynamics of the mixing process are visualized with the aid of fluid particles as rendering primitives (Figure 7). The essential physical properties to be visualized are the velocity field, pressure, temperature

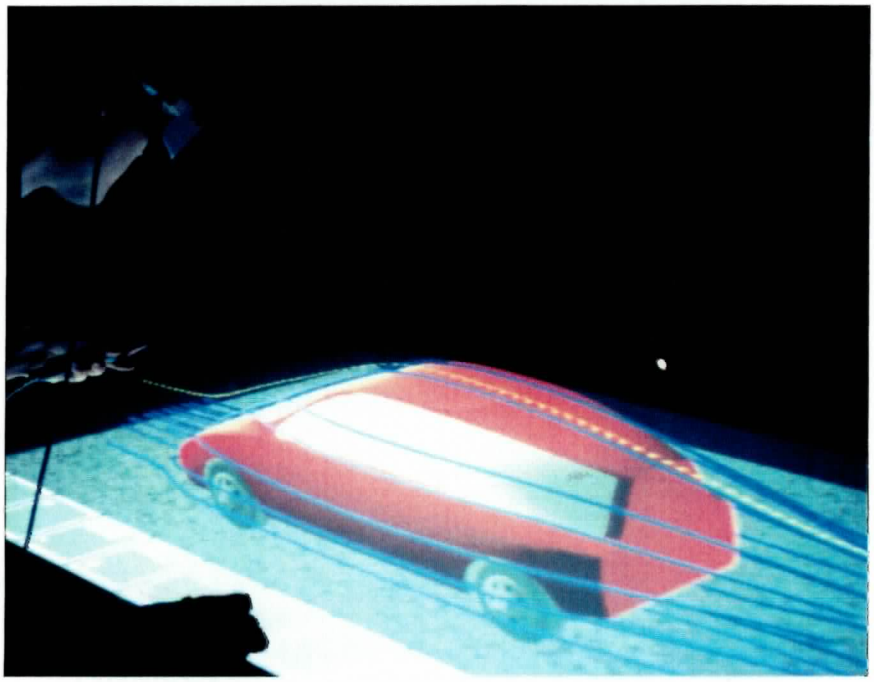

Figure 6: Virtual windtunnel scenario for car manufacturing applications (aerodynamical study model ASMO-II).

and fuel distribution. The mixing process is strongly time-dependent, so the data rate is much higher. The visualization shows the particle flow with color coded temperature during the injection process. These particle paths are precomputed during the finite volume simulation. The current implementation focusses on the interactive real-time 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 serves as a 3D texture on the SGI Onyx rendering system.

Basic requirements of the virtual environment in this application domain are a high resolution color display (at least 1280×1024 pixels) and the capability of real-time 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. The RW environment is designed to fit the daily working situation of engineers in car manufacturing.

Architecture and design applications

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

An architectural model is shown on the workbench, in our case the area around the buildings of our research institute (see Figure 8). In front of the table two architects

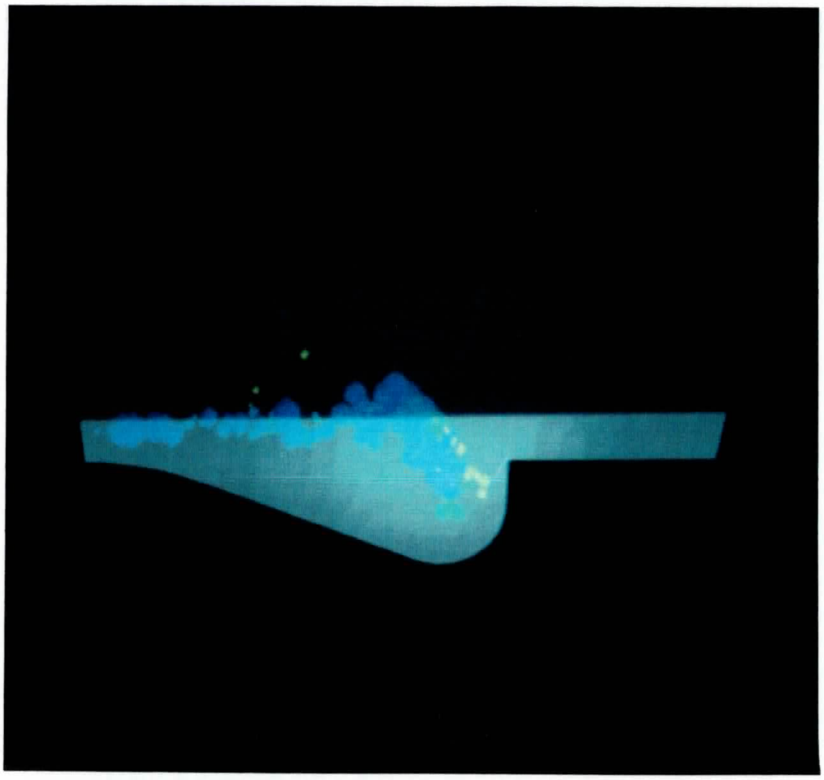

Figure 7: Mixing process

discuss the model, moving around buildings or other objects, such as trees in the virtual world. Additionally, lightsources can be set by the glove device 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 buildings or 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. We think that typical walkthrough experiences can be much better simulated by HMD or CAVE systems.

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 common virtual environments such as: real-time, high-resolution rendering of stereoscopic images with realistic appearances

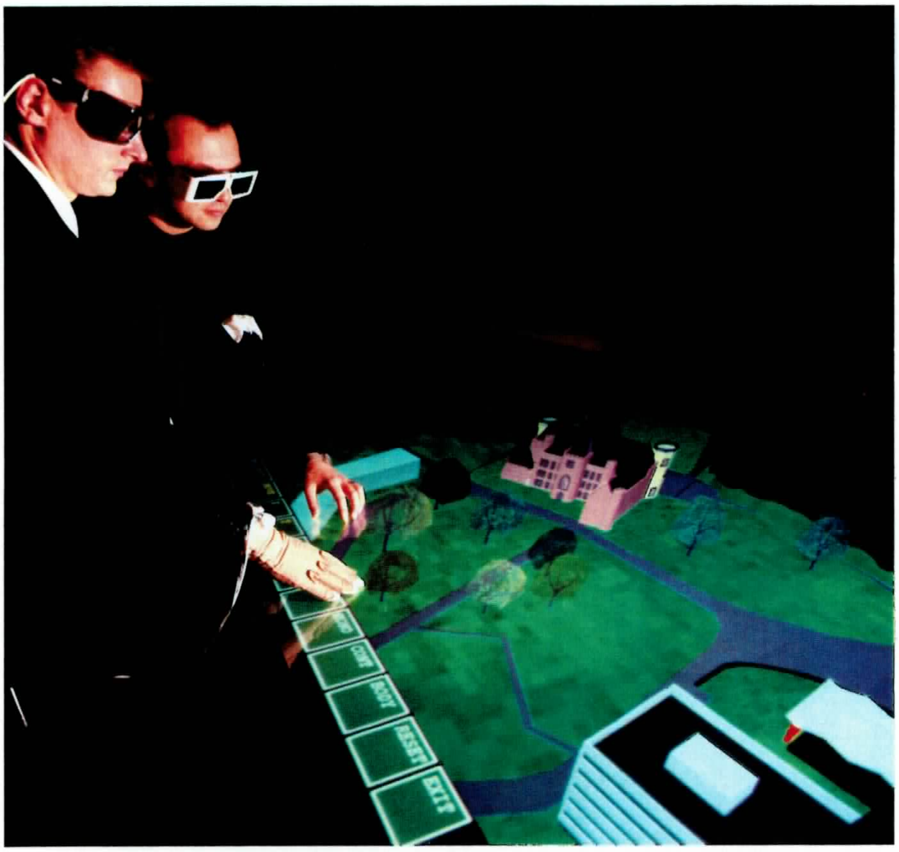

Figure 8: Architectural planning scenario

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.

6 Acknowledgments

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