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How Scientific Visualization Can Benefit from Virtual Environments

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Virtual Environments (VEs) represent a powerful novel way of Man Machine Interaction. Scientific Visualization, on the other hand, copes with large amounts of numbers which are often hard to interpret. It is expected that new interaction techniques will enable applications of Scientific Visualization which have not even been thought of yet. The availability of Virtual Environment techniques has initiated discussions about the benefits of VEs for Scientific Visualization and also led to some experiments on VEs in Scientific Visualization.

This paper discusses the strengths and weaknesses of VE techniques regarding Scientific Visualization. Four examples of Scientific Visualization using Virtual Environments are reported. They include a visualization system for finite element and voxel data, the visualization of meteorological data for lay audiences, a training simulator for arthroscopic examinations, and sonification in a dataflow visualization system as well as in VEs.

We expect that the work reported here will promote research on a symbiosis of the two fields to the benefit of both of them.

1. Introduction

Virtual Environments (also called Virtual Reality or Cyberspace) are regarded as one significant step forward in Man-Machine Communication. Following non-interactive, command-driven and graphical-interactive sytems, Virtual Environments now allow an easy-to-understand presentation and more intuitive interaction with data. The computer internal worlds, consisting of data and processes, represent various aspects of a natural environment or even a totally artificial world outside any human experience.

The main building blocks in Virtual Environments – presentation, interaction, and simulation [13] – require realtime performance. The integration of visual, auditory, and further stimuli are evidently needed in future Man Machine Interaction.

The first generation of peripherals and systems for building Virtual Environments like gloves, helmets, and commercial software packages are now widely available. Many applications [21] – not only architectural design – are going to use and evaluate available VE tools. As the accuracy, usability, and effectiveness of this new technology are still insufficient, many application requirements are adjusted according to the capabilities of VE components.

Current research [14, 23] in this area is established at various levels of immersion and interaction – from desktop virtual reality to fully immersive systems. Research activities aim to overcome the limitations and to improve the acceptance of VE techniques. New paradigms in computer-supported human communication are under development.

The Fraunhofer Institute for Computer Graphics (Fraunhofer IGD) completed the first R&D projects in interactive Scientific Visualization in 1988, just around the time when the NSF report [24] was published world-wide. Available high-end computer graphics hardware has allowed to apply techniques in Scientific Visualization to so called 'real world problems', i.e., data from engineering, medicine, etc. with a considerable complexity and a huge size [3]. Preserving interactivity even with 'gigasets' of data has been one foundation in all application projects in Scientific Visualization. Methods of parallel computing on multiprocessor workstations or workstation clusters have led to remarkable results in enhancing the performance of the visualization pipeline [17, 11]. Thus, it was possible to interact with this real world data directly, i.e., to use the data itself as echo objects in interaction [16]. By means of techniques like the Virtual Trackball, interaction devices have provided six and more degrees of freedom which allow manipulation in three-dimensional space.

The application of Virtual Environment techniques to Scientific Visualization was fostered at IGD by a strategic initiative of the Fraunhofer Society, which established demonstration centres for Virtual Reality in three different institutes [22]. These demonstration sites are fairly well equipped with VE devices and high end graphics workstations, and provide consultancy in VEs and integration of VEs in industrial applications with small and medium size companies.

The availability of VE techniques has initiated discussions about the benefits of VEs for Scientific Visualization and also led to some experiments on VEs in

Scientific Visualization.

In this paper we reflect the discussions and present some of our initial experiments. The experiences made in some application projects will also be reported and discussed.

2. Virtual Environment Techniques for Scientific Visualization

In the following, we will review some Virtual Environment (VE) techniques and their relevance for Scientific Visualization (SciVis).

Many years ago, Richard Hamming stated that 'the purpose of (scientific) computation is insight, not numbers.' *Scientific Visualization* has the goal to leverage existing scientific methods by providing new scientific insight through visual methods. Since the first R&D initiative in Visualization in Scientific Computing [24], a variety of algorithms and visualization techniques has been developed, evaluated in different application areas, and integrated into visualization systems. Research has increased the number of alternative visualization techniques that can be used to investigate physical and technical phenomena. As a result of advances in recent graphics hardware, large application data sets now can be visualized interactively [19].

Virtual Environments are defined in [6] as 'realtime interactive graphics with three-dimensional models, when combined with display technology that gives the user immersion in the model world and direct manipulation'.

Normally, immersion is achieved either by wearing a head mounted display (HMD), using a binocular omni-orientation monitor (BOOM), or by moving within a room with – probably several – large screen projections, as for example in the CAVE system [10]. Sound may be used to add acoustic impressions. Haptic information like in a force feedback device can further contribute to the impression of being immersed in a real situation. On the other hand, some people use the term Virtual Environments for any kind of somewhat realistically looking 3D realtime graphics. And indeed, Ivan Sutherland in 1965 wrote the historic phrase: 'One must look at the display screen as a window through which one beholds a virtual world'. It seems that a realistic image on a screen would be sufficient to meet Sutherland's ideas. Actually, he already anticipated today's VE output devices, because in the same paper he wrote 'Indeed, in the ultimate display, one will not look at that world through a window, but will be immersed in it ...' [29].

Another important issue for VEs is interaction. This is expressed in [6] by the terms 'realtime interactive' and 'direct manipulation'. Common devices used for interaction in VEs are data glove, spaceball, or mouse.

Even though most people are thinking of head mounted display and data glove when hearing the term Virtual Environment, a definition solely based on these two classes of devices would be far too narrow. Actually, long before the term Virtual Environment was in use, aircraft simulators and other systems which we now call VE systems were already common.

Our definition of Virtual Environment goes back to Sutherland's basic ideas which did not necessarily demand a head mounted display or the like. If immersion is considered to be a crucial requirement for a VE system, then we define immersion as the impression of being in a realistic situation, even if it is actually a simulation. Therefore, we use the expression Virtual Environment for any artificial environment (i.e., simulated by a computer) which in some respect behaves as if it was real. This definition comprises not only generic VE systems but also all kinds of simulators, like for example the arthroscopic training simulator which will be discussed later. According to [13], computer graphics systems can be classified by using three 'dimensions' (see Figure 1):

- type of *presentation* to humans: single events (static presentation), event sequences (animation of discrete states), and realtime events (continuous animation);
- type of human *interaction*: no interaction, interactive (abstract, symbolic commands or user interface devices), and immersive (direct, intuitive input);
- type of computational model which is generating *data*: geometry only (geometry is not derived from other modalities), static semantics (geometry is derived from static data, e.g., isosurface of a static field of scalar values); and dynamic semantics (geometry is derived from dynamic data, e.g., isosurface of a time dependent field of scalar values).

Often, the data which leads to geometry are generated by a *simulation*. Therefore, the three discrete values of the last dimension could also be described as: no simulation, offline simulation, and online simulation.

According to this model, Virtual Environments are the most demanding discipline in computer graphics. VEs involve continuous realtime presentations of complex virtual worlds, new immersive interaction paradigms, and the simulation of various phenomena (dynamic semantics). Evolving SciVis applications also stress the importance of these three categories.

Next, we will investigate presentation, interaction, and simulation in regard to Virtual Environments and Scientific Visualization.

Presentation in a VE is mainly done visually. The range of output devices spans from head-mounted displays, BOOMs, and large screen projections to desktop monitors. Realistically looking images are produced using shading and texture mapping techniques. In most cases, stereo vision is utilized in order to facilitate spatial perception. Realtime rendering is crucial in order to achieve a realistic behaviour of the system. Modern rendering hardware produces textured and shaded images at reasonable frame rates for up to 30 000 polygons in realistic applications. Holographic displays are another emerging technology for visual presentation.

In SciVis, stereo rendering is an effective visual clue for the recognition of complex shapes. However, for 3D user interaction with scientific data, i.e., for exact positioning tasks, we found stereopsis being less efficient than methods using 2D projections and a frame of reference [18].

Acoustic presentation is a feature which will soon complement the visual presentation techniques in many VEs. With audio hardware and system software readily available, it is now possible to take the next evolutionary step and use acoustic simulations to enhance virtual worlds. Today, the use of sound in VEs is often limited to the triggering of fixed, prerecorded samples or to continuous background music. The ultimate goal of acoustic simulation in VEs is the generation and subsequent computation and auralization of sound propagation in a virtual environment in realtime. Even though appropriate hardware devices for realtime auralization are not yet available, the development of such devices is under way, and in short time this technology will become generally available [4]. Preliminary investigations have shown the benefits of acoustic rendering for Scientific Visualization [1, 2].

More exotic kinds of presentation like force feedback subsystems and tactile displays are slowly being developed and customized, as, e.g., in the Cricket device [12]. Olfactory and gustatory simulation with computer controllable devices is still subject to experimentation [30].

Interaction is another crucial feature for VEs and SciVis. In conventional Scientific Visualization, three classes of interaction can be identified: interaction for configuration and control of the visualization pipeline, which is mainly done by means of graphical user interfaces (GUIs), interaction for viewpoint control, and interaction with application data, also called semantic interaction [16]. Since scientific data in general is three-dimensional and often time-dependent, the space in which a user navigates is also multi-dimensional. Software techniques have been developed which allow the mouse to control more than two dimensions, the most important one being the virtual trackball for rotation in three dimensions. The user can imagine a glass sphere around the object on the screen. The object can then be rotated arbitrarily by rolling the sphere with the mouse cursor. Besides rotation, zooming and dragging can be controlled with the mouse directly within the 3D graphics window.

In VEs, modern devices like six-dimensional trackers and balls or gloves are used which are inherently multidimensional and provide users with intuitive input capabilities. It may seem that such new devices fulfill the demands of complex scientific data perfectly. Nevertheless, they are applied very seldom to interactive scientific visualization. We experienced that conventional input devices such as mouse and dials are sufficient for user interaction with data in conventional scientific visualization [18]. Currently, there is no real alternative to such devices. This may be caused by the fact that semantic interaction usually requires exact positioning. On the other hand, in emerging SciVis applications where the user grabs objects similar to an assembly simulation or in Virtual Environments, especially the dataglove and the spaceball allow for faster interaction [15]. The low positional accuracy of these devices will be overcome by improved device technology and by the aid of object constraints.

Simulation of objects with realistic behaviour is a key feature of all computer based training systems. In high quality aircraft simulation, the complex behaviour of a plane must be simulated according to a mathematical model of the physics of the plane. The results of this simulation are visualized by means of flight instruments, a realistic view of the outside scenery, sounds, and even movements of the 'cockpit'. In walk-throughs – today the main application which is generally considered to be 'virtual' – there is only little simulation so far. Normally, the building is static, and only seldomly objects may be found that are changing or that can be manipulated. At our lab in Darmstadt, we have incorporated into our Virtual Environments physically based kinematic modelling, e.g., drawers that can be opened, moving objects like a car moving through the scene, light sources and TV sets that can be switched on or off, and even multiple users who can see each other and interact in VE [5].

Simulation also is a key feature of Scientific Visualization. Normally, SciVis is being used to visualize measured or precomputed (i.e., simulated) data. The aim of SciVis is to gain new insights, to 'see the unseen'. The interactive investigation of scientific data can be facilitated by realtime visualization with steering of the data source [24]. This means that the results of numerical computations are presented continuously during the calculations, and that the user may interrupt the process, change the simulation parameters, go back to an earlier time step, and continue the computations.

In single examples like NASA Ames' *Virtual Windtunnel* [9] or NCSA's experiments of integrating VE techniques into the application builders IRIS Explorer and AVS [28], VE techniques have already shown to be useful for the analysis of complex data. Rather than relying almost exclusively on human cognitive capabilities, they engage the powerful human perceptual mechanisms directly. Still, VE techniques are applied very seldom to interactive scientific visualization; conventional visualization systems like AVS or IRIS Explorer normally do not support VE devices. One important reason besides high costs and still low reliability is that these novel input and display devices cannot be combined with conventional user interfaces, i.e., 'point and click' GUIs, for the configuration and control of the visualization systems. On the other hand, new applications incorporating SciVis (like the merging of ultrasonic data with video which is being done at the University of North Carolina [7]) are emerging, which demonstrate the benefits of combining Virtual Environment technology and Scientific Visualization.

We conclude that VE technology did not get widely accepted for the use with conventional visualization systems, but that it will enable a new generation of tools to aid scientific investigation by means of simulation and immersion in Virtual Environments.

3. Examples

In the following sections we present some examples of work done in Darmstadt on the field of the symbiosis of VEs and SciVis. They include such diverse applications as material testing, weather visualization, medical training, and sonification.

The work illustrates that the investigation of scientific data can indeed benefit from VE techniques and it suggests further directions of research.

3.1. The ISVAS visualization system

ISVAS [19] is a visualization system developed at IGD. It is a turnkey system for the visual analysis of finite element and voxel data. As with most visualization systems, the aim is not to build up a Virtual Environment around the user, but to provide an interactively controlled visual presentation of scientific data. The interactions to be performed are mainly rotation, translation, and scaling, all in 3D. With these basic operations, the viewing is controlled and different objects, such as cursors, slices, etc., are positioned in the scene. Today, the most wide-spread input device is the mouse. The mapping of the 3D operations onto the 2D mouse – such as the virtual trackball for rotation – is acceptable after some practice, but is not very intuitive for the occasional user.

Therefore, we included the spaceball and the dataglove as alternative input devices to support a more natural interaction in 3D space with these devices (see Figure 2). We also included stereo view in order to improve the spatial impression in the generated images.

At first glance, the dataglove seems to be a very intuitive device for interaction in 3D. Objects are grabbed and manipulated just as in real life. Still, we registered disadvantages in using the dataglove:

- The positional accuracy is very low.
- The hand is obstructed by the sensors and cables, which make it difficult to handle mouse and keyboard, to make a note on a piece of paper, or even to answer the telephone.
- You have to put the glove on and carry it, which is very inconvenient compared to just stretching out the hand and moving the mouse now and then.
- You cannot rotate and move the hand arbitrarily.
- You get tired from moving around the hand in the air.

While the first two points might be eliminated by improvements in the hardware, the next three points are disadvantages inherent to the dataglove.

Being a spatial extension of the mouse, the spaceball has proved to be a comfortable device. The six degrees of freedom correspond very intuitively to the 3D operations used in ISVAS.

Our experience with stereo view is that the perception of depth (normally indicated by shading only) is very much improved, but it is still difficult to position a 3D cursor in space. Further aids, e.g., a stage around the objects or multiple views from different directions, are a more valuable support for these interactions than stereo.

Our subjective conclusion of the work with ISVAS is that multi-dimensional input devices and stereo view are not sufficient to create a Virtual Environment in Scientific Visualization, but they may improve the interactions. Virtual

Environments as well as Scientific Visualization will contribute to and benefit from the further development of input devices and interaction techniques.

Another similarity between Virtual Environments and Scientific Visualization is realtime visualization with the steering of the data source. Steering is exactly what is done in VEs: The system simulates an environment, receives input from the user, and provides feedback in realtime. One example is the flight simulator, where the pilot steers the simulation by manipulating the devices and perceives the feedback of the system as a causal reaction on his manipulations, just as in real life.

Since the basic concepts of realtime visualization with steering are similar to those of the simulation of a Virtual Environment, each discipline will be able to profit from the research and developments of the other.

Realtime visualization has been realized with ISVAS. Typically, the simulation process is run on a compute server and ISVAS on a graphics workstation. The processes are connected by a network (LAN or WAN). Two modules have been developed to support steering [8]:

- an application-independent user interface module for the simulation program, and
- a data manager that stores the computational results.

By using these modules, an existing simulation program needs only some small modifications in order to be adapted for steering. This way, an interactive analysis of phenomena is achieved rather than an analysis of precalculated data. This presents an important step towards using VE techniques in Scientific Computing.

3.2 Visualization of meteorological data

Scientific visualization plays an especially important role in meteorology. In this field it is almost impossible to extract meaning from the very complex datasets that are generated by simulation models on powerful super computers without visual tools. Meteorologists have been trained to use visualization systems for analyzing their models and the prognosis data. These data can be just scalar data (e.g., temperature, humidity, pressure), vector data (e.g., wind) or multivariate data (e.g., describing clouds). Also, clues can often only be found in data derived from the original simulated values. In order to generate a weather forecast for television audiences, newspaper readers, or airline pilots, the meaning of the datasets and their combination must be understood by the experts and transformed into a presentation that is perceptually effective for the target audience. Here again, visualization tools are very important [26].

In the past two years Fraunhofer IGD has been developing a system for the visualization of meteorological data together with the German Meteorological Office. It supports the scientists in their research work and in their task to visualize the data for lay audiences. This kind of visualization must be intuitively understandable by non-experts with their everyday experience of weather phenomena. We have therefore developed special algorithms for the visualization of clouds. Due to the extremely coarse resolution of the original data, we use fractal functions to generate realistic cloud objects that are still very accurately modeled by the prognosis data. The results of our work are very encouraging and are broadcast daily by a national and a local TV station since January 1993 [25].

Of course, weather has a three-dimensional nature. Even though two-dimensional weather maps have proven to be very effective, local phenomena can be better understood in a three-dimensional perspective. Here we can benefit from VE techniques allowing immersion in complex 3D scenes. Visualizing fractally enhanced volume cloud data over densely sampled terrain elevation data is a very compute-intensive task and we are far away from acceptable frame rates with acceptable quality images yet. Still, our first results are very promising and allow presentations like: 'How would the clouds look like when viewed from an aircraft flying a certain route', or 'What would you see if you stood on that mountain and looked around'. An example is shown in Figure 3.

This kind of visualization is already possible but still too slow. Therefore, we are currently developing special complexity reduction algorithms allowing faster rendering [27]. Immersive presentation strongly supports the intuitive understanding of weather forecasts and is suitable for local effects. However, until interactive television is realized, TV stations have to render such flights of virtual cameras a priori before broadcasting and interactive exploration can merely be done individually in VE laboratories.

3.3 Training simulator for arthroscopic examinations

Arthroscopy is increasingly being used as a diagnostic procedure to reveal changes and diseases, especially of knee joints. The arthroscope, supplied with optics and light source, and the exploratory probe are inserted into the knee joint through two small incisions located underneath the kneecap.

Training the arthroscopic examinations is done by observing an experienced surgeon in an operating theatre before the trainee is using the arthroscope and the exploratory probe for the first time. For surgical training a standard training system (a synthetic replica of the knee joint) is used. The main shortcoming criticized by surgeons is the insensitiveness of the plastic replica with regard to the incorrect handling of the instruments. Often, too much physical strength is applied.

An alternative training system could be a computer supported simulator employing Virtual Environment techniques. Therefore, we developed an arthroscopy training simulator in cooperation with the Berufsgenossenschaftliche Unfallklinik in Frankfurt am Main, Germany [31].

After analyzing and discussing videos and observations of arthroscopic examinations in an operating theatre the requirements for the simulator were specified. Based upon these requirements we developed a fully interactive system by means of Virtual Environment techniques. The system visualizes a three-dimensional computer-generated knee joint in realtime. This model was reconstructed from data of magnetic resonance images.

The 3D interaction is realized by a tracking system (Polhemus FASTRAK System) configured with an electronic unit and three sensors (trackers). The trackers are fixed at the instruments, a replica arthroscope of the same weight and shape as the original and a real probe, and on the lower part of the plastic knee which is used to increase the realism of the simulated examination. The trainee inserts the instruments into the synthetic knee joint and moves them within an electromagnetic field, while the electronic unit of the tracking system monitors the movement within the 'virtual knee'. As this is happening the graphics superworkstation (Silicon Graphics, Reality Engine) continuously generates 10-15 frames per second corresponding to the changes in position and orientation.

The prototype was presented at the 'Frankfurt Sports Medicine Weekend' on December 4 and 5, 1993 (see Figure 4). The weekend included an arthroscopy course for surgeons. This course comprised talks and practical training, which was performed using conventional training systems and the training simulator.

Discussions with the participants of the arthroscopy course, surgeons and trainees, confirmed our work. There is additional work to be done in order to get a more perfect training simulator. Our current efforts focus on a speed-up of the frame rate. Since the presentation in December 1993 we have doubled the speed (from 5 – 8 frames to 10 – 15 frames per second). Furthermore, we will integrate collision detection which had not been activated due to the low frame rate.

Integration of force feedback is very important for the acceptance of the simulator. We have finished a conceptual study concerning the realization of this issue. Based upon this concept we will start developing a prototype of the force feedback simulator in cooperation with the Department of Electro-Mechanical Construction at Darmstadt Technical University this summer.

3.4. Sonification

On the field of sonification – turning data into audible information – two directions of research have been followed in Darmstadt. To begin with, sonification tools were integrated in a dataflow visualization system in order to unite the advantages of a general-purpose visualization system and of sonification to a powerful and universal visual, aural, or audiovisual environment. Furthermore, acoustic rendering capabilities were added to the VR toolkit of Fraunhofer IGD, which allowed the demonstration of several virtual audiovisual worlds.

Visualization is a widely acknowledged discipline to explore vast numerical data by interactive analysis of their visual representations. Sonification increases the bandwidth of Man Machine Communication by one dimension towards a perceptualization platform, which eventually may allow the affection of all human senses. Besides the generation of pure sounds, sonification in combination with visualization can especially help to reinforce the displayed visual information or to give additional information if the visual presentation is already overloaded. A reference model addressing both visualization and sonification has been developed in Darmstadt. The use of audio implies time;

therefore, a concept for handling time in a dataflow system was also elaborated. A number of modules and tools for sonification were designed and realized within the *apE* system. This includes basic tools to create digital audio samples, to manipulate audio samples, to map data onto audio samples, several audio renderers (image source algorithms, particle tracing algorithms, and radiosity-based approaches), and audio players to play the filtered, mapped, and eventually rendered audio samples on existing audio hardware. Examples have demonstrated that the toolkit provides all the necessary tools to enhance visualization with sonification features [1, 2].

The integration of audio features in Virtual Environment applications contributes a great deal to a natural simulation of imaginary worlds. It leads a step further to the ultimate goal to stimulate all human senses and let humans get totally immersed in virtual worlds. The toolkit of IGD provides a convenient and powerful development platform for Virtual Environment applications. Before adding an acoustic renderer to the toolkit, the relationship between acoustic and visual rendering had to be investigated. Acoustic renderers require additional objects like sound sources, receivers, and acoustic material attributes. Visual and acoustic renderers are similar in many respects; both of them operate on geometrically defined scenes. It is the different propagation speed of light and sound which causes algorithmic differences. Several different acoustic renderers were included in the rendering toolkit. They compute parameters which are used by an audio server to manipulate digitally sampled sounds. Applicable acoustic rendering qualities are:

- Sound events, i.e., sound sources can be triggered when a 3D cursor collides with an object having an audio event attribute (e.g., for playing a drum kit with a dataglove);
- Direct propagation, i.e., volume damping, frequency shift for moving objects (Doppler effect), and relative stereo position can be computed;
- Statistical approach, i.e., the current reverberation can be computed in realtime by means of a precomputed global reverberation value;
- Image source algorithm, i.e., the impulse response at an arbitrary listening position can be calculated, visualized, and sent to the audio server for convolution;
- Particle tracer, i.e., arbitrary environments can be processed, unfortunately not in realtime due to its enormous complexity.

Figure 5 shows the visualization of such an acoustic simulation. Here, direction and detected energy of sound arriving at a virtual listener are visualized by direction, length, and color of vectors.

Experience with the toolkit demonstrated that sounds help to significantly increase the degree of immersion for human dwellers in imaginary worlds [4].

Four examples were used to illustrate the experiences that have been made in utilizing VEs for SciVis in Darmstadt. These examples included a visualization system for finite element and voxel data, the visualization of meteorological data for lay audiences, a training simulator for arthroscopic examinations, and sonification in a dataflow visualization system as well as in VEs. The examples prove that Scientific Visualization can indeed benefit from Virtual Environments, especially in novel applications which require a very intuitive way of Man Machine Interaction.

4. Conclusion

In this paper we have explained why Virtual Environments can enable a new generation of tools to aid scientific investigations. We have discussed the strengths and weaknesses of VE techniques with respect to Scientific Visualization by investigating their properties on the fields of presentation, interaction, and simulation.

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FIGURES

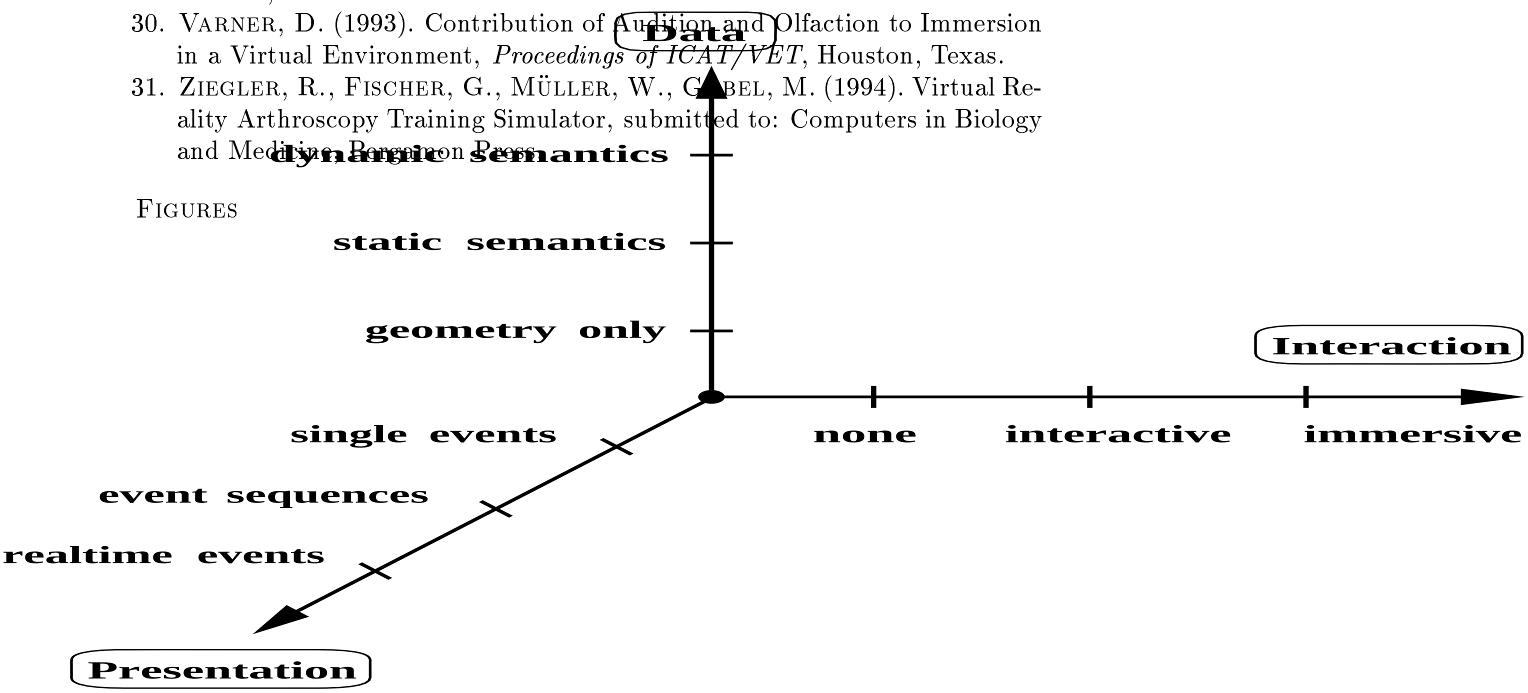

FIGURE 1. Classification of computer graphics systems.

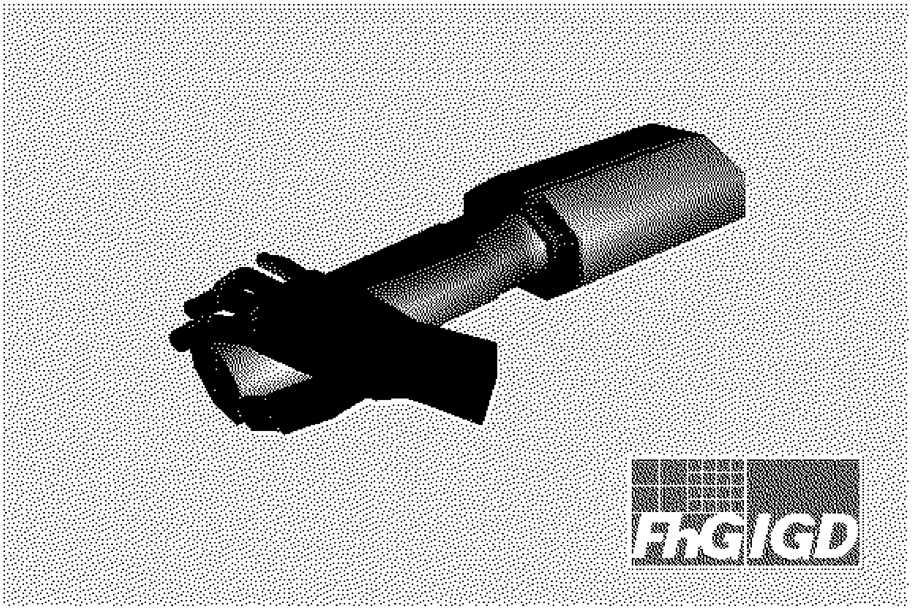

FIGURE 2. Data glove used for the rotation of a finite element data set.

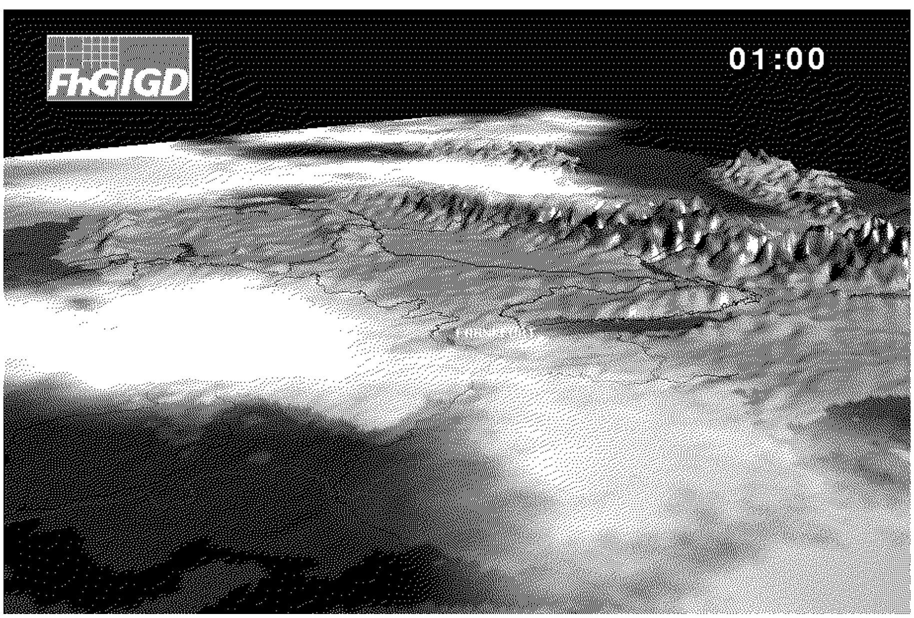

FIGURE 3. Perspective view of a 3D terrain with predicted clouds.

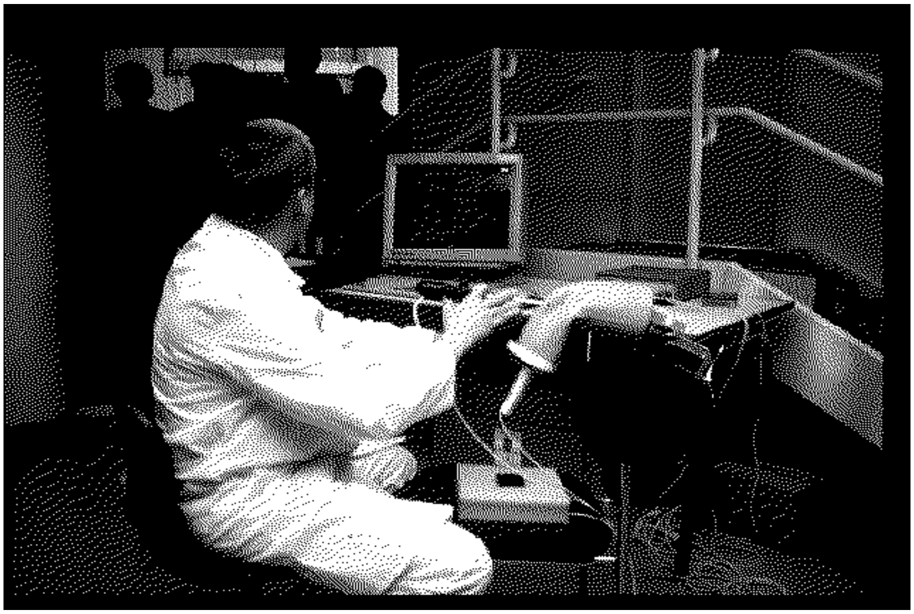

FIGURE 4. Presentation of the arthroscopy training system in Frankfurt.

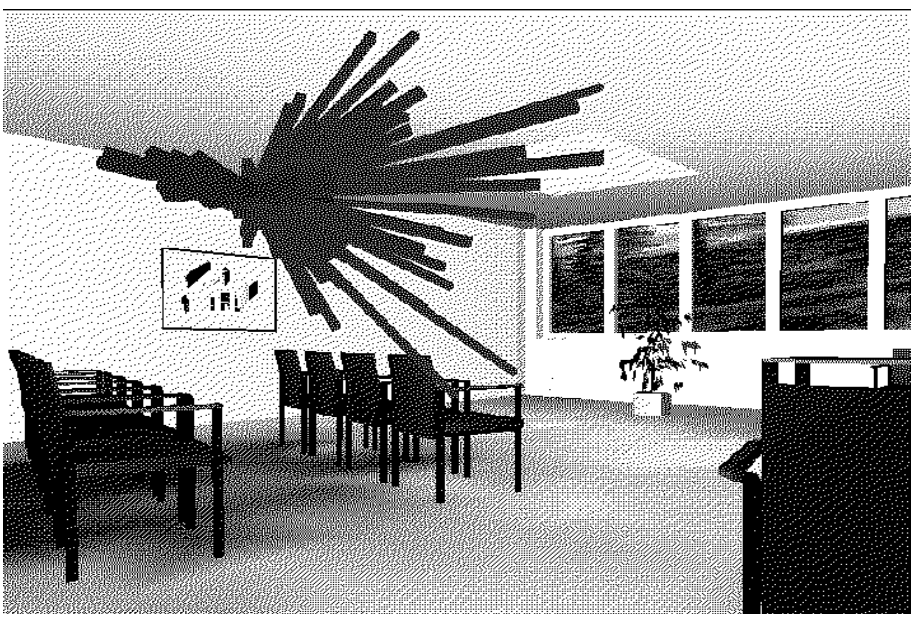

FIGURE 5. VE visualization of an acoustic simulation: Vectors depict