CHAPTER 96

Virtual Reality for Industrial Engineering: Applications for immersive Virtual Environments

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1. OVERVIEW

This chapter focuses on virtual reality (VR) applications in the fields of engineering and industrial engineering. It gives definitions of the main keywords for the field of engineering and describes the hardware and software and the specific human–computer interaction aspects for virtual environments (VE). Some typical applications are specified that show the field-tested use of VR, and the basics for the integration of such applications in the development process are described.

1.1. Virtual Reality in General

By means of VR, an intuitive working environment can be created in which the multiple aspects of human intelligence are addressed. With sufficient perception and interaction qualities to give the user a feeling of intuitive handling of virtual objects, the following VR principles can be attained.

- Visualization, evaluation, and design of 3D objects
- Advancement of creative abilities by free design and communication of imagined objects
- Interactive demonstration of objects and events
- Mediation of (abstract) knowledge based on the user's experiences (e.g., exploring a molecular structure)
- Mediation of skills and training of behavior in dangerous situations and environments
- Knowledge mediation beyond human physical limitations (e.g., exploring how a gasoline engine functions by opening up the combustion chamber)
- Exploration of distant places or past epochs

1.2. Field of Use for VR in Engineering and Science

The main application area for VE is the simulation of objects and processes. This suggests that VE can be used as a presentational simulation technique. Aside from the presentation of perceptible sensory objects, a special use is in the expression of nonmaterial and invisible objects or in the saving of physical products. The presentation can rely on a static scene as well as on a dynamic process. With a pure presentational simulation, the degree of interaction is limited because the emphasis is on the presentation of knowledge. However, with control simulation by means of VE, the user takes a more intensive part in the events, while the qualities of presentation have been preserved. Apart from the use of control simulation for entertainment purposes, uses are in handling critical situations, controlling devices in inaccessible areas, and working with meager resources. The third application type is particularly characterized by its interaction forms, where the virtual objects are not just moved but also used for design simulation. These applications support decision making in the product-development process.

In addition to process simulation, VE systems can be used as mediators for other, generally real, objects. The purpose of presentation of any object is communication. Furthermore, VE can be used as a medium for human–machine interaction. Communication with an unreal object, such as another virtual representation, is possible. Finally, it is possible to integrate virtual information within a real environment.

A third dimension of possible VE use is telepresence applications, which include simulations that do not take place at the application location, as well as communication. These applications are founded on real spatial distances. Application areas are differentiated into two areas: telepresence, which is a spatially distanced presentational simulation, and teleoperation, which is a type of simulation for a manipulation or design purpose.

1.2.1. Virtual Prototyping

Among other things, the duration of the development process is determined by the number of the physical prototypes that are required for evaluation of the desired product properties. Virtual prototypes are defined as a computer-based simulation of a technical system or subsystem with a degree of functional behavior that is comparable to corresponding physical prototypes (Haug et al. 1993).

The visualization of virtual prototypes calls for the processing of the data with dependence on the visualization techniques. Apart from purely realistic visualization, complexity-reducing models and symbolic visualization are used as well. Mixed models of both methods are most widely spread. Metaphors for visualization of simulation results, for example, are used in FEM analysis (overlaying of paint leveling) or the representation of paint coat thickness in robot simulation (Brown 1996).

Research activities for the evaluation of virtual prototypes with techniques of VR are encountered in the investigation of flow response of flying objects (Bryson et al. 1997) and automobile chassis. The geometry model is overlaid with the results of flow simulation such as isosurfaces or as paint particles. The user can freely move cutting planes or virtual trails of smoke. Investigation of the capability for assembling components is also found in aircraft construction and vehicle construction, including the evaluation of the free construction room available, accessibility, and the ergonomic design of manual assembly workplaces.

Apart from the evaluation of the product properties, a further-reaching use of virtual prototypes also requires consideration of the production processes of the products.

Aspects of asynchronous and synchronous object management in a distributed environment and the data models for the manipulation of lead time have thus far been in the foreground in systems for designing objects in a virtual work environment. Here, the data models are oriented by existing CAD standards or they focus on application protocols for the product data model STEP, with these protocols still to be developed. These systems are also not fully immersive, but they are monitor based in connection with relevant 3D input tools (e.g., space mouse, trackball). Handling aspects of virtual prototypes in an immersive VE have been studied, for example, at the University of Wisconsin-Madison (Dani and Gadh 1996).

1.2.2. 3D Representation of Complex Data

The 3D representation of complex data is applied to the examination of comprehensive geometry data records, such as in architecture or in the scientific visualization field, the representation of mathematically computed data. In the visualization of building data in architecture, the architect would like to walk through the virtual building together with the customer and detect design errors. Research and development work is conducted at a large number of research institutions and enterprises. The visualization of mathematically computed data has the goal of rendering simulation results visible, audible, or tactile. Outstanding work on this subject has been done by NASA Ames Research (Bryson et al. 1997). For evaluation of the outside shape of flying objects, they simulate the flow response in a virtual wind tunnel.

1.2.3. Simulation of Work Sequences and Activities

A near-reality perception (immersion) in a virtual environment is used to plan and investigate work sequences and activities. Immersion is achieved by 3D representation of information in real time by integrating several human senses, with the user perceiving himself or herself as part of the scene. The interaction differs from the input devices used so far in that direct intervention in the 3D space is possible (Durlach 1997). The goal is to adapt the work environment to human responses and physical capabilities. Simulation of the work environment and human interaction with work surroundings is necessary to produce a near-reality perception. Ergonomic investigations can be conducted with subjects without a physical test setup.

1.2.4. Substitution of Complex Physical Prototypes and Tools

Physical prototypes are used for testing and evaluation of product properties in the early development stages of product development. VR permits testing and evaluation to be conducted in virtual prototypes. The objective is to avoid physical prototypes if possible. Research is being conducted in the automotive and aerospace industries (Leston et al. 1996). Apart from purely design-oriented tasks, efforts are also being made to conduct physical materials tests, such as crash tests, in virtual prototypes. Additional approaches deal with the production engineering view of prototypes and products up to the planning of production facilities and production plants. These also include approaches to the substitution of complex resources for the support of production, such as in the production of cable harnesses in the aerospace industry (Ellis et al. 1997).

1.2.5. Modeling and Control of Business and Production Processes

Apart from product- and production-oriented spheres of application, VR technologies are also used in product modeling and control. Research approaches can also be encountered in information technology, for the analysis and maintenance of communication networks, and in the modeling of production engineering processes.

1.2.6. Cooperation in Virtual Work Environments

In addition to spoken language, human communication is based on expression by the body (gestures) and the face (miming). Research in near-reality virtual work environments investigates human communication in immersive VR environments. This research is focused on computer-supported cooperative work (CSCW) (Pandzic et al. 1996), the mapping of human gestures and movement, and the realization of synthetic behavior of virtual human beings (Shawver 1997).

1.3. Virtual Reality in the Product-Development Process

The use of computer-based tools and methods in the development process is essential with respect to quality, time, and costs. The general business conditions are similar worldwide: product life cycles are declining drastically, and technological leadership of the highest possible quality is required in order to react to constantly increasing innovation dynamics. Engineers have to decrease the time for construction and evaluation of the prototypes. The mainly computer-based development of products using 3D CAD systems offers many advantages in optimization of time, costs, and quality, but it leads quickly to a restricted, reduced perception of the product during the development process. Therefore, digital models require an immersive VR-based working environment to improve the perception of the computer-based models.

Another factor is that new processes like rapid product development (RPD) focus on the short time between the final determination of the construction and the start of sale. Although the complexity of most products and of the product development process is growing, the first sketches must be more detailed and the basis for valid decisions should be guaranteed. Therefore, the use of VE has two main goals: to enhance the degree of freedom of predefinition and to achieve a higher level of elaboration in the early development phases for better decision support.

Therefore, the use of immersive projection technology (IPT) has two main goals: to enhance the degree of freedom of the construction constraints and to achieve a higher level of elaboration in the early development phases for better decision support. Figure 1 shows how these goals are benefitted by the use of VE.

Tools and methods that are used in VE and that permit information to be obtained about the product in the early development phases offer attractive optimization potentials (time, costs, quality) in engineering. Among other things, in the foreground here are product aspects and features that essentially permit qualitative information to be obtained (e.g., formal aspects) and can be primarily assessed by evaluation (e.g., motion spaces in connection with capability of assembly). Human interaction with the virtual prototypes and human perception and immersion in the VE is decisive for handling the tasks on hand (Figure 2). The verification of qualitative information has normally been possible so far only on the basis of real, physical prototypes.

2. DEFINITIONS

2.1. Virtual Environment

An application-orientated definition that might state the most accurate minimal demand describes VE systems as a combination of computer-based display and interaction techniques.

Ellis (1995) defines a virtual environment as a synthetic, interactive, illusory environment perceived when a user wears or inhabits an appropriate apparatus, providing a coordinated presentation of sensory information in imitation of a physical environment.

All VE applications are founded on the generation, perception, and manipulation of naturalistic or abstract virtual worlds without any physical equivalent. Objects existing within virtual worlds can possess various qualities and behaviors. Examples are graphics, sound, and force feedback. By multiple addressing of the human senses, the attempt is made to generate the greatest possible intuitiveness of virtual environments; VE can be experienced through visualization, marked out by 3D object representations and real-time-orientated interaction modes.

To distinguish VE from the multitude of computer-based visual simulation techniques, the following minimal requests must be fulfilled:

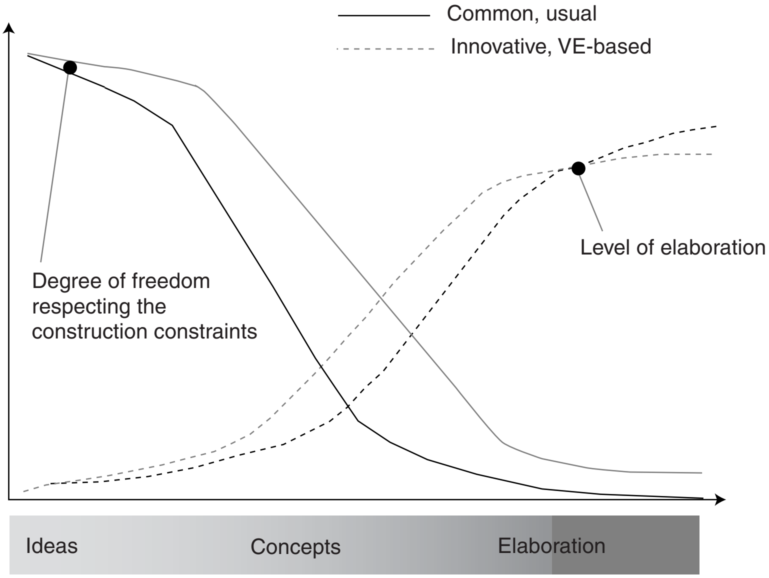

Figure 1 Benefits of use of VE in the Development Process.

- Graphical display dependent on the position and orientation of the user.
- 360° visualization complies with all three coordinate axes
- Realistic 3D behavior of the modeled objects
- The most possible intuitive interaction modes with objects, adapting to human experiences and behavior
- Object manipulation in all real or requested degrees of freedom
- Quasi-real-time-orientated object response

VE systems can be defined as computer-based information technologies for interactive, real-time orientated simulation and multisensory representation of objects, processes, and their results. With

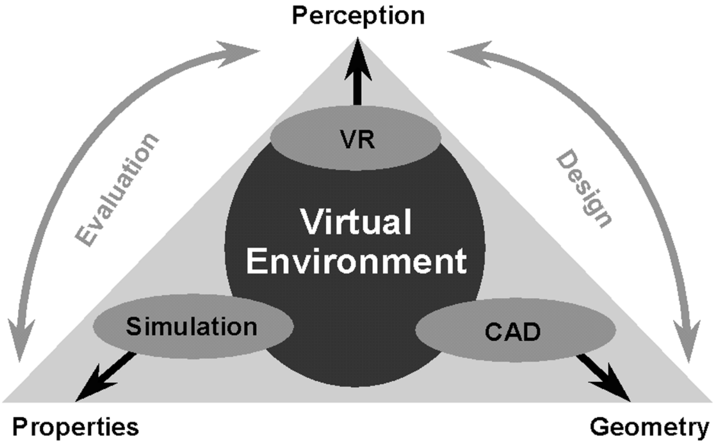

Figure 2 System for Evaluating and Designing Virtual Prototypes.

the surmounting of conventional input and output interaction forms, the user should be given the impression that he or she is situated in a virtual environment. The human's central cognitive abilities, such as the interpretation of visual data and the recognition of complex structures, are thus supported.

To describe computer-generated worlds, terms in addition to *virtual environment* have been established, such as *virtual reality, artificial reality, telepresence,* and *cyberspace*. Generally accepted is the use of *virtual reality* as an umbrella term for computer-generated, interactive 3D scenes, *cyberspace* as a place of communication connecting several users together, and *telepresence* for an experience that overcomes space and time. *Virtual reality* tends to suggest the perception of a meticulously detailed computer-generated duplicate of a natural environment. In contrast, *virtual environment* stresses the secluded nature of the application, whose abstract representations depend more on the user's ideas than on real models. *Virtual reality* suggests utopian visions, and hence for reasons of precise description, experts prefer *virtual environment*.

The degree of immersion indicates the extent to which a user is tied to a virtual environment. Immersion can be described as an opportunity for real-time-orientated perception and interaction. Immersion is characterized by the believability of the environment. Immersion has a technical dimension, a content-representative dimension, and an individual–psychic dimension. These dimensions each contribute to an immersive experience.

2.2. Digital Mock-up

Digital mock-up (DMU) is a digital product description for development, design, and manufacturing. The aim at present is to enhance the DMU in order to replace physical mock-ups with a digital one that will require only one verification prototype at the end of the design process. DMU is based on the management of a complete product model. DMU functions for the assembly, fitting, and operation of a virtual product, simulation of tolerances, ergonomics, and flexible parts will be available. In parallel, DMU checks the virtual product with regulation constraints. DMU is required to be an integral part of design systems, available from any location and from any activity point of view. Virtual reality techniques will be used for the stereoscopic visualization of the DMU.

2.3. Virtual Prototypes

Virtual prototypes are defined as a computer-based simulation of a technical system or subsystem with a degree of functional behavior that is comparable to corresponding physical prototypes. The visualization of virtual prototypes calls for the processing of the data in dependence on the visualization techniques. Apart from purely realistic visualization, complexity-reducing models and symbolic visualization are used as well. Mixed models of both methods are widespread.

2.4. Rapid Product Development

Rapid product development (RPD) shortens the feedback control cycles concerned with product data generation and the associated management processes. RPD exploits the potential of modern information and communication tools in order to support the necessary dynamic cooperation structures. Development times are systematically shortened by means of a holistic integration of man, organization, and technology. The learning processes can be systematically relocated to early product development phases. As a result of generative methods of production and virtual reality, physical and virtual prototypes can be made quickly available.

2.5. Augmented Reality

Augmented reality (AR) combines real worlds/objects with virtual worlds/objects. AR is a novel approach to the interaction between human and machine. It is possible, for example, to view information using a head-mounted display. The information is displayed context sensitive, which means that it depends on the observed objects, such as a part of an assembly. The engineer can now display job-related assembly data while viewing the real object.

3. VIRTUAL ENVIRONMENT HARDWARE AND SOFTWARE

3.1. Structure of VE Systems

In order to be able to design and use effective VE systems, it is necessary to understand the technical concepts related to virtual environments, to be aware of the limitations of the available technology, and know the design approaches that lead to the creation of successful virtual environments. Although there are many VE systems in use, areas open for research are not just the system and device design, but also the ground use concepts. The basic functioning of a VE system is shown in Figure 3.

3.2. Hardware

To create immersive experiences in VEs, VE systems integrate a combination of several hardware technologies. These technologies can be grouped under the following categories:

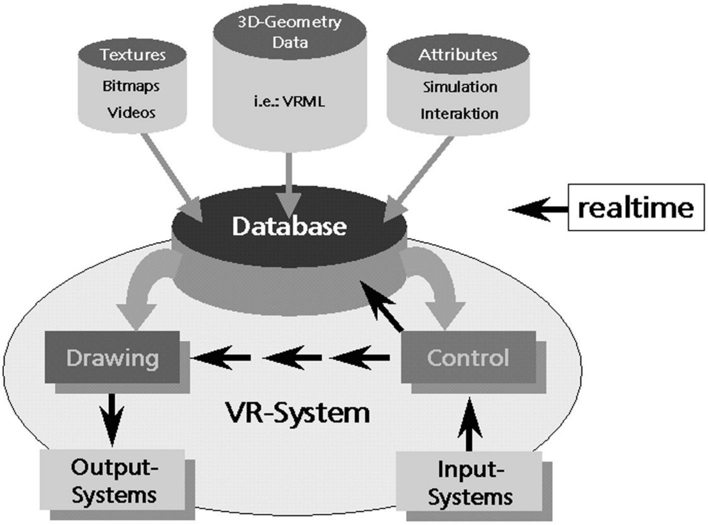

Figure 3 Basic Structure of a VR System.

- *Display systems:* present the virtual environment to the user.
- *Position and orientation systems:* track the user's position and orientation in the virtual environment. They are also used for interaction purposes.
- *Interaction and manipulation systems:* provide manipulation of the virtual environment.
- *Computation systems:* perform the computations required for the generation of a virtual environment.
- *Networks:* allow integration of several distributed user systems in one common environment.

3.2.1. Display Systems

The main elements of VE interfaces are displays that mediate visual, acoustic, and tactile sense stimuli. Of essential significance are visual and acoustic displays.

Visual displays are devices that present the virtual environments to the user. The degree of immersion given by a particular VE system depends greatly on the visual interface display. Several kinds of visual displays are currently available: monitors, head-mounted displays (HMDs), head-coupled displays (HCDs), and projection systems. All of these systems are capable of producing wide-angle stereoscopic views of the scene, although in some cases monoscopic vision is also used.

HMDs, which are the most broadly used visual displays in immersive VE systems, and HCDs place a pair of display screens directly in front of the user's eyes. In HMDs, the screens are mounted on a helmet that the user wears while staying in virtual environments. The HCD is like a pair of binoculars freely attached to a flexible swivel-arm construction, which can be easily handled by the hand through open space. Both HMDs and HCDs are coupled with a tracking system to determine the viewer's position in space. The virtual environment is displayed in stereo from the user's point of view, which serves a high degree of immersion; users are completely surrounded by the virtual environment. Other kinds of visual displays are projection-based systems. In such systems the user's position and actions are tracked and the corresponding virtual scene is projected onto large screens.

Acoustic displays can be used to provide feedback concerning the virtual environment. Sound plays an important role in localization and interaction. Due to the application of simple audio in many other areas outside of VE, it is known as a mature technology. Synthesizers creating, mixing, and reproducing sounds and systems for speech in- and output have been made available.

3.2.2. Position and Orientation Systems

Tracking is a critical component of an immersive environment. Tracking includes the measurement of the user's head position and orientation as well as the measurement of other body parts, such as the user's hand and fingers. The continuous measurement of the user's head position and orientation is of high importance because it is used to produce the correct environmental view from the user's point of view, which is critical to obtaining a high degree of immersion. Tracking of body parts and movements allows interaction with and control of the virtual environment to take place.

In principle, tracking is suitable for any technology. Thus, the three-dimensional position and orientation of an object can be determined as free of delay and reliable. Electromagnetic, kinematics, acoustic, optical, image work processing, and inertial procedures find use for tracking tasks. Currently available body-tracking systems fall into two classes (Bryson 1993):

- *Position tracking:* devices that detect the absolute position and usual orientation of a tracker in 3D space
- *Angle measurement:* devices that detect the angle of bend of some body part; usually found in data gloves to measure the angle of finger joints

3.2.3. Interaction and Manipulation Systems

Interaction and manipulation systems are devices that allow manual exploration of the virtual environment and the manipulation of virtual objects. These devices, functionally based on a tracking system, measure the position and forces of the user's hand and other body parts and can apply forces to the user to produce the sensation that the virtual objects are real (Cruz-Neira 1993).

Interaction and manipulation devices have been classified as:

- Pointing and selection devices
- Force and torque feedback devices
- Tactile devices
- Devices to produce stimulus, such as temperature

The best-known interaction device is the data glove. After having been calibrated to the user, the data glove allows the computer to determine the user's hand gesture, such as fist, open hand, or pointing. Often the hand's physical position in a 3D space is also determined. The glove's coordinates are overlaid into the virtual environment, where the physical glove position controls a 3D virtual hand in this environment. The virtual hand can be used to pick up virtual objects, push virtual buttons, and so on (Iovine 1994). Numerous interface devices also exist, such as the free-flying joystick and spaceball, which were developed into 3D devices from conventional interface devices, as well as systems for tactile and force feedback.

Another interface technology for effective control and interaction in VEs is speech control. Speech control in virtual environments will facilitate tasks and exploration. Not tied to tapping onto a keyboard or moving, a control device will free the user's hands and add to the feeling of immersion (Iovine 1994).

3.2.4. Computation Systems

Computation systems are the computer hardware used to control the overall operation of a virtual environment. Computer hardware has to handle several tasks: generation of graphics for the scene, computation of the state of the environment, and control of input and output devices. In a VE system, all these tasks have to be integrated and synchronized.

3.2.5. Networks

Networks are used to exchange data between different virtual environments. They lay the foundations for distributed VE systems. Distributed VE systems make it possible to connect people located in different places to let them take part in a joint communication and design process. With the appropriate tools, such systems can be powerful platforms for interdisciplinary work, independent of location. This is known as computer-supported cooperative work (CSCW).

3.3. Software

An internal computer functional hierarchy exists for processing information input and generating appropriate output. Essential functions of this hierarchy are represented by the modules of modeling, simulation control, and rendering. Built onto appropriate hardware structures, this functionality is realized by software technology.

3.3.1. Modeling

The virtual world of an application is constructed principally through modeling. As a rule, object data are converted from CAD data and completed through color and surface data. In addition to geometric description, modeling also includes function modeling, beyond the CAD applications, in which the total number of functions and the geometric free degrees of a respective object are determined.

The structure of geometric objects can be described through parameters (object data). The sum of the computer-stored object data produces the internal computer representation of real objects. The mathematical model of a real object is composed not only from data structures but also from algorithms that operate on these structures. It forms the base for all built-up modules, such as simulation control and rendering.

3.3.2. Simulation Control

During VE application, the arrangement of objects is constantly calculated by putting the contents of the databases in relation with the interaction instructions of the user or the behavioral parameters of autonomous objects. Simulation control is closely linked to the communication of the data processing. The basis for coordinated running is real-time management.

Simulation requires the determination of certain functions. Therefore, interaction parameters or collision identification have to be defined. Complex simulations require very high computing performance, which may lead to bottlenecks within real-time management.

3.3.3. Communication

Communication includes data transformation, that is, the coordination of data transfer between input/output devices and simulation control as well as data exchange between users and units involved in a multiuser system.

With the data transformation, the transformation software interprets the interaction instructions of the user and passes the input commands to the simulation control, where the real-time orientated computation of the virtual environment occurs. Additionally, the data representing the virtual environment are reconverted by the transformation software into appropriate interface signals and presented as simulation output. Thus, the data transformation primarily functions to transfer data between the user interfaces and the simulation control.

Within a multiuser application, the communication coordinates the data exchange between the active participants and units involved in a network. The real-time-oriented data exchange informs all participants about relevant interaction processes as well as the actualization of the databases.

3.3.4. Rendering

The term *rendering* or *drawing* includes different procedures of the transformation of parametric data models into discrete images and sounds. Therefore, rendering is part of the communication within data processing, but due to its complexity and importance in VE it is specially dealt with. The performance requirements of real-time rendering are high. In VE applications the performance bottleneck is mostly in rendering, both visual and acoustic.

The visual presentation normally occurs with a pair of images, which must be rendered with a minimum frame rate of 20 frames/sec in order to avoid picture disturbance.

Image generation is based on lighting models, which are divided into two types: local and global. Local models take into account the reflections from single surfaces, independent of the environmental lighting situation. Global models take into account the independence of lighting and reflections and therefore seem more realistic, but they are more difficult to generate.

The acoustic presentation within a virtual environment orients itself towards the geometry and surface formation of the room being modeled. Acoustic simulation is suitable for two methods. First is the image source method, which calculates virtual sound inclusive of the reflection behavior of the surfaces being modeled. From this, the sound energy coming towards the receiver can be defined. Second, with the particle-tracing method, the transmitted sound impulses are registered by detectors, where the impulse response can be measured.

4. HUMAN–COMPUTER INTERACTION FOR VE

4.1. Visualization Basics

The light transmitted from a source reflected by an object is sent to the eyes. By refraction and collection, the light is concentrated on the retina, where the photoreceptors are embedded. The nerves are then aroused, and the signal is escorted along the optical track and analyzed by the brain. The eye accommodates itself to the distance of the object being seen. By adapting to dark and light, the eyes are able to change their acuity within a wide range. Color vision results from the stimulation of the retina by light of various wavelengths in the range of 400–780 nm.

When a 3D object is seen, a separate 2D image is projected onto each retina. The two images are converted into impulse patterns in the brain, where they are united to create a 3D object. The convergence angle between the eyes' axis and the accommodation is used to determine the distance of an object from the eye.

Visual perception is the most important for feedback in a virtual environment. Optical information is presented by optical displays. Along with the application, display devices with various inserted performance profiles are used, making it possible to create anything from simple monochrome graphics and line models to a photorealistic rendering. The specifications of the visualization technologies, which can be varied in depending to the application, are discussed below.

4.1.1. Resolution

Optical resolution is the angular size of an object that can be individually resolved. Resolution is defined as the angular size of a picture element. Resolution increases as the angular size of the picture element decreases. Optical resolution is closely related to screen resolution, the number of pixels on a screen, which in turn determines picture element resolution. The effective optical resolution is determined not only by the picture element resolution of the screen devices but also by the optics through which the screen is viewed (Bryson 1993).

Eye resolution depends on many factors, including color, brightness, contrast, and length of exposure. On the axis, resolutions of around 5 arcmin are required to reach the region of peak sensitivity. Acuity increases rapidly as the object moves outside the central 2° region. It is principally sufficient only to provide the central field of vision with detailed pictures because the natural resolution of the eye in the periphery strongly decreases. At 10° off-axis eccentricity, acuity drops around 10 arcmin (Helman 1993).

However, the marginal areas are particularly sensitive to low light intensities and movement. To achieve natural resolution capabilities, screens with 6000 picture lines are suitable. For a convincing visual display with a field of view of 150°/60° at a distance of 250 mm, a resolution of, ideally, 9000 × 3600 pixels is recommended.

4.1.2. Stereoscopic Visualization and Depth

Stereoscopic visual presentation usually takes place using a pair of pictures with a slightly shifting convergence angle. The limit of stereo vision typically occurs at a binocular disparity of 12 arcsec. The methods of stereoscopic visual presentation can be divided into time parallels (both-eye simultaneous visual presentation) and time-multiplexed systems (non-perceptible alternating visual presentation). Time parallel stereoscopic systems produce the displacement of the optical convergence axis either by different monitors for each eye or by two half pictures differentiating in color and perspective, which are looked at through toned or polarized 3D glasses. Time-multiplexed systems insert optical or mechanical called shutter systems for the viewing of alternating pictures displayed on a monitor.

Three-dimensional visual perception through object-differentiated accommodation cannot occur with an HMD, because the monitor has a flat surface. When the eyes look at stereoscopic computer-generated imagery, their accommodation and convergence often do not match because they must focus on the screen or the image plane defined by the optics of an HMD with an angle for stereoscopic view dictated by the rendered images. Without proper calibration (or a monoscopic system), neither focus nor convergence may reflect the actual position of the virtual object relative to the viewer. Because of these inconsistencies, many users of stereoscopic systems have trouble fusing stereo images. To place the images at infinity, thereby making convergence and focus match closely for distance vision, collimated optics can be used. Computer graphics applications that do not need to depict the depth of scale acurately can artificially adjust the parallax to allow more comfortable viewing. For virtual environments requiring close-up manipulation of objects or accurate registration of virtual objects with the physical world, all variables affecting stereo viewing should be considered. Size, image distance, and overlap of the system must be chosen carefully to match the task and operation distance.

However, other solution approaches try to realize the adaptation of depth with changing of the focus. The eye's focus is measured by means of a laser beam reflected by the retina, and in consequence the depth of focus is followed by image visualization (Aukstakalnis and Blatner 1992).

4.1.3. Field of View (FOV)

Each eye has approximately a 150° FOV horizontally and 120° FOV vertically. The binocular overlap when focused at infinity is approximately 120°. With VE display devices, a wide field of view is very desirable for conveying a feeling of immersion. For HMDs a 120° horizontal and 60° vertical FOV is minimally recommended. The trade-offs for higher FOV are lower effective resolution and usually more distortion in the periphery of the picture. Distortion can be avoided by using complex optics. However, distortion is a big problem with see-through HMDs because the world provides a reference for "straightness". With the relatively small FOVs of HMDs, large overlaps of more than 50% have been found useful.

4.1.4. Brightness and Luminance

Including dark adaptation, the eye has a dynamic range of around seven orders of magnitude, far greater than any current display device. The eye is sensitive to ratios of intensities rather than to absolute differences. At high illuminations the eye can detect differences in luminance as small as 1%. Brightness is a basic precondition for the perception of objects.

Brightness is the available luminance for each picture element. A typical HMD based on a cathode ray tube (CRT) can display no more than about 400 perceptible luminance levels. Sufficient brightness is particularly a problem for liquid crystal displays (LCD).

In order to minimize disturbing light conditions and differences of contrasts between the physical environment and the virtual simulation, high brightness is especially important for see-through HMDs.

4.1.5. Contrast

Contrast is the dynamic range of the luminance that the display supports. Contrast is important to the perception of structure in an image. Low-contrast systems are difficult to interpret. Low-contrast and low-brightness displays do not serve a high degree of immersion. With use of screen displays, a 5:1 contrast ratio for scenery and 25:1 for light points is recommended.

With LCDs, the display brightness and contrast depend greatly on the viewing angle. The display viewing angle is characterized as the angle between the normal to the display surface and the line between the center of the display and the user's eye. For high image quality, the viewing angle should be as small as possible.

4.1.6. Color Saturation

Color is a significant feature of visual images. The quality of color can be characterized in terms of the decomposition of a color signal into three primary components. Usually these components will be red, green, and blue, the primary colors, measured by their luminance. Alternatively, color components could include the hue, luminance, and value components.

In display systems, color is usually attained by grouping pixels into sets of color components. For example, a red pixel, blue pixel, and green pixel are grouped into a triple that comprises one full-color picture element. While this method works when the optical pixel resolution is very high, in wide-field displays the individual component pixels are easily individually visible. Another method of attaining color, called time-multiplexed color, is to use a monochromatic display screen with three rotating colored filters, one for each primary color. According to the activated filter, the monochromatic image with the illumination of the correspondent colored filter is displayed.

The quality of the color signal depends on several aspects, such as quality of color component pixels. The dynamic range of the luminance value for each component will determine the full range of colors that can be achieved.

Apart from color displays, monochrome displays are in use for several purposes. In general, monochrome displays offer higher resolution for an equivalent price.

4.1.7. Masking

A display quality issue closely related to color is the problem of masking, or nonabutting pixels, which occurs when the pixels are separated by a blank space. Masking is a problem because wide-field optics magnify the display screen and so magnify the space between the pixel elements. To avoid the problem of visible pixel elements and masking, the image in wide-field displays is often intentionally degraded, which is usually done by a diffusion screen that blurs the pixel.

4.1.8. Performance

In order to avoid picture disturbance, the frame rate must at the least be 20 frames per second. The frequency at which modulation is no longer perceptible varies from 15 Hz up to around 70 Hz for high illumination levels. Bright displays with large FOV can require frame rates up to 85 Hz. In order to minimize movement dizziness, the perceptional latency must be below 0.1 seconds.

4.1.9. Refresh Rate

The refresh rate is the time required for the picture elements to change state (on or off). These times need not be the same. Typically, a pixel takes longer to go off than to go on. If the refresh time of a pixel is too long, ghosting effects will occur in rapidly changing images.

4.2. Visualization Systems

Depending on the grade of immersion and the extent of the interactions, graded concepts from fully immersive VEs down to extended reality can be realized. VE applications for entertainment purposes are intended principally to simulate secluded fantasy worlds. Although development at the beginning relied almost exclusively on fully immersive concepts, today, because of the shortcomings of those concepts, an increasing number of partly immersive VE system applications are being developed.

4.2.1. Fully Immersive VE

With a fully immersive VE, the user wears a head-mounted display (HMD) equipped with headphones and a visual stereo display directly in front of the eyes. The user is visually and acoustically sealed off from the physical environment and primarily perceives impressions the virtual environment.

HMD fully immersive display is made up of two color monitors that project the image directly in front of the eyes and a lens system that widens the image to the natural field of view. Because the convergence angles, the screen arrangement presents a certain appearance of depth.

4.2.2. Projection VE

With projection VE, stereo pictures are projected by means of a special projection system onto surrounding walls. Projection VE systems allow the user a higher degree of free movement because 3D glasses are the only device that has to be worn. Such a system make it possible to link up several users within a VE application. However, orientation and interaction within the virtual environment is more difficult because of the system's low grade of immersion.

For an example of projection VE, see Cruz-Neira et al. (1992), who describe the CAVE system (Audio Visual Experience Automatic Virtual Environment).

4.2.3. Augmented Reality

With augmented reality, semitransparent data glasses are used, which make it possible for computer-generated objects and information to be linked by superimposing them with the perception of the physical environment. Parts of the physical environment remain perceptible at the same time that virtual elements contribute to an enrichment of information.

4.2.4. Monitor VR

In contrast to immersive VE systems, monitor VR portrays a low-priced alternative for 3D visualization of virtual worlds. As with projection VE, the user wears 3D glasses, which give him or her a steroscopic view of the virtual world on a monitor. The user's head movements are measured by a tracking system. The tracking data are acquired by the computation of the orientation-dependent displayed vision. Monitor VR makes the viewing of virtual objects from different directions and distances possible. A decided advantage of monitor VR over fully immersive VE is the possibility of simultaneous interaction with the physical environment. In addition, in contrast to head-mounted displays, present monitors make substantially higher visual resolution available. Because monitor VR is limited to a visual frame, only a slight feeling of immersion is possible.

4.2.5. Responsive Workbench

Responsive workbenches enable direct interaction with virtual objects appearing in physical environments. At a responsive workplace, several users move around a table with a glass top. By means of stereoscopic visual projection from the under side of the table, 3D virtual objects are constructed that appear to the users as if they were resting on the workbench. The users perceive the virtual object and the workbench as well as the individual person and colleagues. Responsive workbench applications are used in medicine and architecture (Krüger and Fröhlich 1994).

4.3. Methods for Human–Computer Interaction

Foley and Silbert (1989) define a human–computer interface as the determination of all user inputs into a computer, the determination of all computer outputs to the user, and the determination of sequences of inputs/outputs made accessible to the user.

The fundamental design principle of VE interfaces is to support human mental processes through an extensive communication and interaction environment and therefore increase the range of human handling and decision making. Following from these principles is the reduction of the degree of enforced handling sequences and the use of a computer for establishment and expression of relations. According to Brooks (1988), from these principles the following differentiated design criteria for the development of user interfaces and computer-based tools comply with ergonomic system design can be derived:

- Three-dimensionality of the modeled objects
- Direct manipulative and intuitive interaction instead of formal interaction
- Interactivity rather than sequence professed routines
- Multisensory stimulation rather than purely visual perception

These requirements derive from the basic idea that human–computer interaction should be comparable to human communication by means of speech, gestures, or body movements. For human access to a computer, all the human sensory channels should be included in the interaction, if possible.

The principal technical challenge in the design of interactive VE systems is in the development of human–computer interfaces, which make it possible to convert internal data structures into sensory-perceptible representations that possess consistent and (for the user) understandable behavior. In the same way, development of devices that translate human movements into computer commands.

In the context of VEs, generic modes of human–computer interaction can be classified into formal language interaction, natural language interaction, direct manipulative interaction, and gesture interaction. These interaction modes are complemented by combined interaction.

4.3.1. Formal Language Interaction

Formal interaction languages are classified into programming languages, command languages, and formal query languages. With command languages, the meanings are predominantly laid down in the vocabulary. An accurate, distinguished volume of available commands and parameters exists. The meaning of a command arises from the sequence and the relative position within an expression. Interactions based on formal languages are technically effective but are unfamiliar to most users. Because formal languages must be learned before they can be used, they are suitable only for a limited number of users. Programming languages are established for system implementation and form the basis of all other interaction languages.

4.3.2. Natural Language Interaction

Natural language systems can use conventional methods of electronic data processing or interfere with knowledge-based systems. In the framework of human–computer interaction, natural language is an adequate means for expressing references to objects, actions, and abstract facts. Natural language offers possibilities of expressing things that can be expressed by other forms of interaction only incompletely or with a large expenditure. The use of natural language in user interfaces increases the number of possible users considerably, particularly unpracticed users. Spoken language, however, changes quickly and cannot be called up in format as written language can. When analyzed, natural language proves inefficient and inaccurate and is manipulable and applicable only with selected dialogs.

Natural speech interaction occurs by means of appropriate input/output speech devices. The technical precondition for speech input/output is voice recognition. Voice recognition systems are classified into speaker-dependent and speaker-independent systems. Speaker-dependent systems, which are capable of achieving a high command count, are trained by the individual who uses the system. The most common drawback of this approach is that the system responds accurately only to the individual who trained the system. A speaker-independent system is trained to respond to a word, regardless of who is speaking. Therefore, the system must respond to a large variety of speech patterns of the target word. The command word count is usually lower than the speaker-dependent word count (Iovine 1994).

Special hardware and software for speech output exists that enables one great amounts of acoustic information to be efficiently stored and reproduced. As yet, the quality of synthetic speech is insufficient because the generation of correctly accentuated and pronounced speech has not been satisfactory achieved.

4.3.3. Direct Manipulative Interaction

Direct manipulative interaction techniques, which are applied with graphical user interfaces, make use of familiar metaphors of daily life. The dialogue of direct manipulative interaction techniques is based on a permanent visual presentation of all relevant objects and function undertaking by single-stage reversible operations. The impacts of actions on the relevant objects are received on a direct visual feedback. Direct manipulative systems make easy learning, use, and extension of system functions possible. The syntax of direct manipulation shows a clear, standardized structure of objects, functions, and attributes. The steps of dialogue with direct manipulation are slight in their complexity and range, as with natural or command languages. Disadvantages of direct manipulative systems are high implementation expenditures and the impossibility of activating objects that are nonvisible on a graphical user interface.

4.3.4. Gesture Interaction

Gesture interaction can be defined as a command-based tool kit that allows the user to interact through nonverbal, nonsymbolic commands and instructions, using gestures, hand signals, and movements. A special kind of gesture interaction is manual interaction. Manual interaction forms are distinguished by grips and movements of virtual objects, corresponding to a physical environment. With the application of natural and intuitive gesture interaction modes, improvement of efficiency of human–computer interaction is aimed at.

The naturalism of gesture interaction forms results from the inclusion of human sensory characteristics and abilities as well as the integration of gestures, which have been culturally conditioned. The quality of a gesture, in particular manual interaction, is orientated towards maximal usability of adaptability and dexterity of the human hand. Consequent allocation of hand movements and accompanying actions contributes to the understanding of gesture interaction.

Gesture interaction makes the specification of certain commands and parameters with high expressive abilities possible—for example, pointing out directions, gripping objects, controlling complex kinematics movements, and parameterizing object qualities. Trivial gesture interaction is easy to learn and does not assume linguistic knowledge. A further advantage is the directness of gesture interaction, in that the hand serves as an immediate medium.

With gesture interaction, every command must be represented by a certain hand gesture clearly distinguishable from other gestures. Particularly for complex commands and control processes, not enough gestures are available, so that gesture interactions based on arbitrary gestures are inefficient. Discrete values and vague expressions are scarcely. Complex gesture interaction, such as for shaping and design applications, has proven somewhat inaccurate and applicable only with selected commands.

In addition, for gesture interaction within the control process, sensory feedback is an essential decision-making criterion.

4.3.5. Combined Interaction

Combined forms of interaction do not represent generic interaction modes, but rather an application-oriented combination of existing interaction modes, primarily gesture, direct manipulative, and speech input.

The isolated use of some interaction modes often leads to a one-sided application and performance profile. With the symbiosis of gesture-based, natural language and direct manipulative forms of interaction, the scope of human–computer interaction and the functionality of the information input can be increased, making it possible to maximize usability and efficiency.

The interaction modes applied within virtual environments in the historical context of human communication are not new. In fact, the tendency to limit communication to screen and keyboard, driven during the last decades by computer technology, will be reversed and communication will be shifted back to a human standard.

5. VR APPLICATIONS

5.1. Virtual Prototyping

Prototyping includes numerous technical, methodical, and organizational measures, from concept formulation to a finished draft. In the face of increasing task complexity and shorter innovation cycles, the various requirements, design areas, methods, and planning participants can however only be integrated in a common development, design, and communication process with considerable computer support. For this task, computer-based planning and design tools are needed that possess a high degree of stimulation at their human–machine interface. VE technologies are well suited as the methodical foundation for the prototyping.

5.1.1. Immersive Design Review

3D CAD systems generate continuous surface and volume descriptions often referred to as solids. VR rendering systems deal with polygons or, in some cases, voxels. The process of converting CAD data to VR data is called tessellation. Tessellators exist for all major CAD formats, including the neutral formats IGES, VDAFS, and STEP. Different problems occur with this conversion:

- Insufficient model quality (wrong-side normals, cracks through not considering topology, LODs too coarse)
- Unneeded model complexity (wrong SAG values, improper algorithms, tessellation of invisible details, LODs too fine)
- Poor image-rendering performance (poor culling structure, missing LODs, unneeded model complexity)
- Missing data structure (loss of logical structure, trade-off to culling structure)
- Typical CAD conversion problems with neutral formats such as IGES or VDAFS.

Data exchange properties other than geometrical ones (surface description, constraints, kinematics, etc.) is by no means standardized. Importing those properties into a VR system currently requires a proprietary interface. However, for consistent and efficient work, all properties considered need to be imported and altered definitions need to be sent back to the CAD system.

Performance problems with complex model data will likely be handled by intelligent software algorithms (occlusion culling, motion LODs) in the near future.

One example of CAD data visualization is the virtual design review, which is used to evaluate, compare, and optimize exterior car designs in very early stages of the development process. The benefits gained are clear: saving physical design models can dramatically reduce time and costs. In Figure 4, a picture of a nonexistent car can be seen. Key factors for the designers in this type of application are very realistic rendering, especially of surface properties (in this case SGI′s ClearCoat technology), and the ability to render a very high number of polygons.

Scaling accuracy and high resolution for good visual perception are another must. This example was created using the Fraunhofer IAO software Lightning (Blach et al. 1998). The application properties and demands here are:

- *Goal:* evaluation of design/surface/proportions
- *Data:* surface geometry (very complex), surface appearance (very realistic)
- *Visualization:* highest possible projection quality, 1:1 scale, medium field of view power wall or CAVE (especially for interior models)
- *Graphics power:* highest possible
- *Application level:* basic

Of course, it is not possible to replace all physical design prototypes with virtual ones, but even saving of one physical prototype represents a great success for the first generation of virtual design

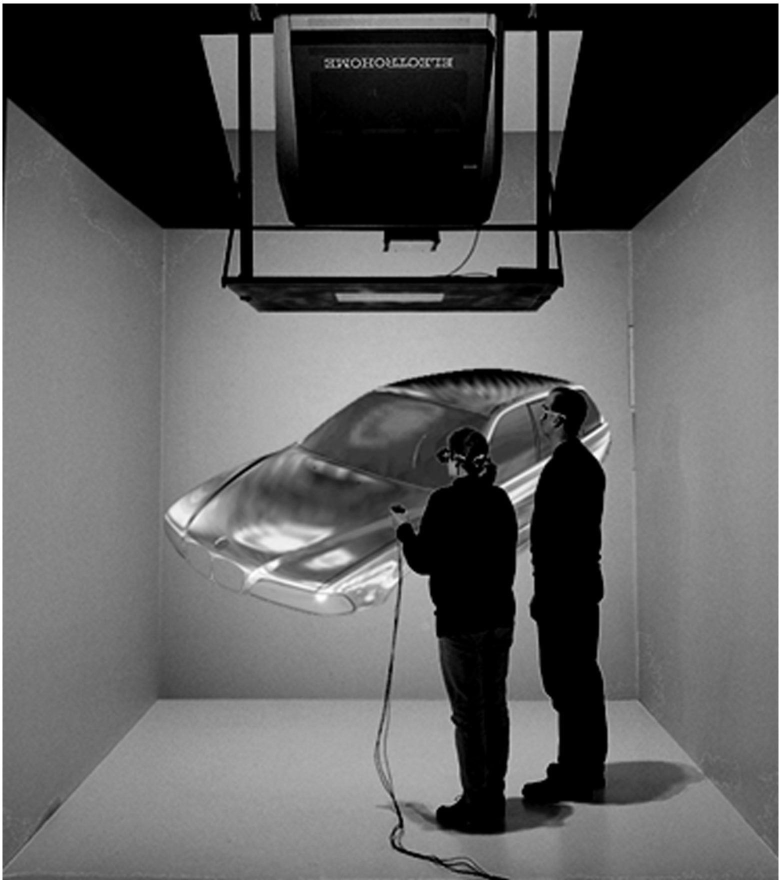

Figure 4 Example of Immersive Design Review.

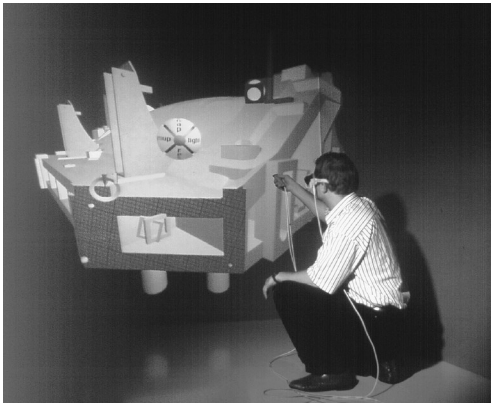

Figure 5 Tool Evaluation.

review tools. High-resolution power walls matching a 1:1 scale model seem to be the best output device here.

5.1.2. Tool Evaluation

The main task in this application example was to give specialized engineers a tool for improving the construction and evaluation process with sheet metal forms. The application was developed by Fraunhofer IAO for BMW:

- *Goal:* evaluation of CAD data
- *Data:* surface geometry (medium sized, CATIA solids), surface appearance (simple)
- *Visualization:* medium field of view, 1:1 scale, medium projection quality, single-wall rear projection or multiwall rear projection
- *Graphics power:* medium
- *Application level:* complex

The evaluation of tools can, in some cases, be greatly simplified by completely replacing the physical prototype with a virtual one.

Automatically creating a VR data set from the CAD solids reduces the preparation time for a tool review session to minutes. The required level of image-rendering speed and projection quality in this special application is medium, so the actual IPT system is moderate in price.

Special care has been given to creating an easy-to-learn, easy-to-use, and therefore simple interface for end users working with the application up to six hours a day. The main functionality of the application is as follows:

- Cutting of the data to explore collisions, etc.
- Annotation function to mark critical areas
- Snapshot function for automatic documentation (creating HTML pages for the intranet)
- Movie player for animating FEA data
- Virtual light source with dimmer function
- Measurement of sizes and angles

5.1.3. Immersive Postprocessing

The field of simulation (mostly FEM and CFD) deals with engineering and the natural sciences, which in many cases are to complex to be discussed exclusively on the basis of numerical values or texts. Multidimensional data sets need adequate visualization and presentation. An interdisciplinary discussion of simulation results is supported by a spatial, multidimensional representation of the data using VR-based techniques. An example of an industrial VR-based postprocessing application can be seen in Figure 6, where the thermal comfort in a car cabin is analyzed by examining the results of a stationary fluid flow simulation (using STAR CD).

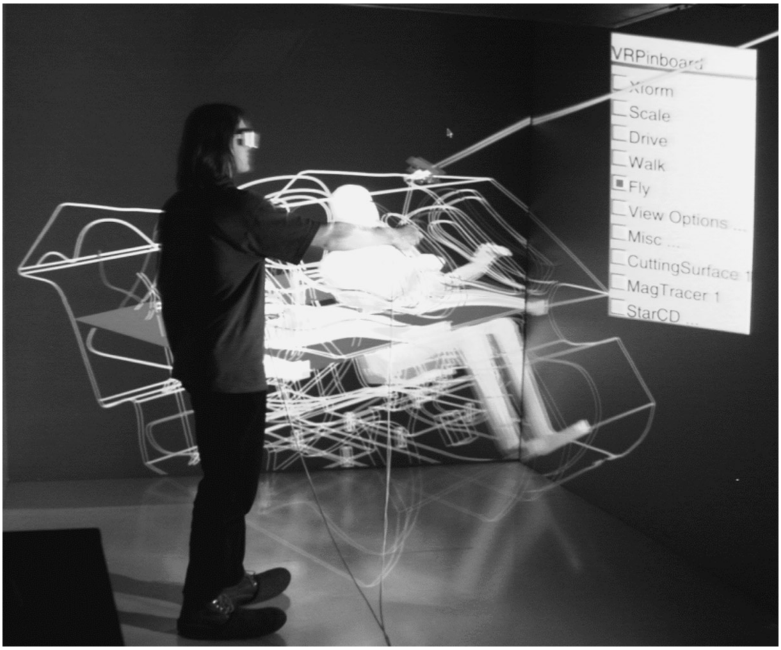

Figure 6 Fluid Dynamic Visualization in a VE. (*Source:* HLRS and Fraunhofer IPA)

- *Goal:* visualization of simulation results
- *Data:* surface geometry (simulation meshes), surface appearance (simple), visual appearance of simulation data (high resolution, medium quality)
- *Visualization:* high field of view, variable scale, medium projection quality CAVE
- *Graphics power:* high
- *Application level:* complex

The software used, COVISE (Rantzau and Lang 1998), is in principle based on a data flow paradigm found in visualization packages. In contrast to most pure data flow packages, COVISE uses the concept of data and function objects (modules) that can be arbitrarily distributed across machines. The data objects are transferred between hosts using special request broker modules (one for each host). A central controller module is responsible for proper synchronization and execution of a module network constructed beforehand in a visual application builder.

5.2. Process Simulation/Factory Planning

Near-reality perception (immersion) in virtual environment is used to plan and investigate work sequences and activities. Immersion is achieved through 3D representation of information in real time by integrating several human senses, with the user perceiving himself or herself as part of the scene. The interaction differs from input devices used so far in the possibility of direct intervention in the 3D space. The goal is to adapt the work environment to human responses and physique. The simulation of the work environment and the interaction of humans with their work surroundings is necessary to produce a near-reality perception. It is possible in the surroundings to conduct ergonomic investigations with subjects without a physical test setup.

Figure 7 shows a snapshot of a robot simulation for an automotive welding cell, DaimlerChrysler A-Class manufacturing plant in Rastatt, Germany. This application is based on the Fraunhofer IAO software Lightning attached to a kinematics simulation package from Fraunhofer IPA:

- *Goal:* visualization of the production process
- *Data:* surface geometry (medium), surface appearance (medium), logistic data kinematics
- *Visualization:* highest possible field of view, 1:1 scale, medium projection quality CAVE
- *Graphics power:* high

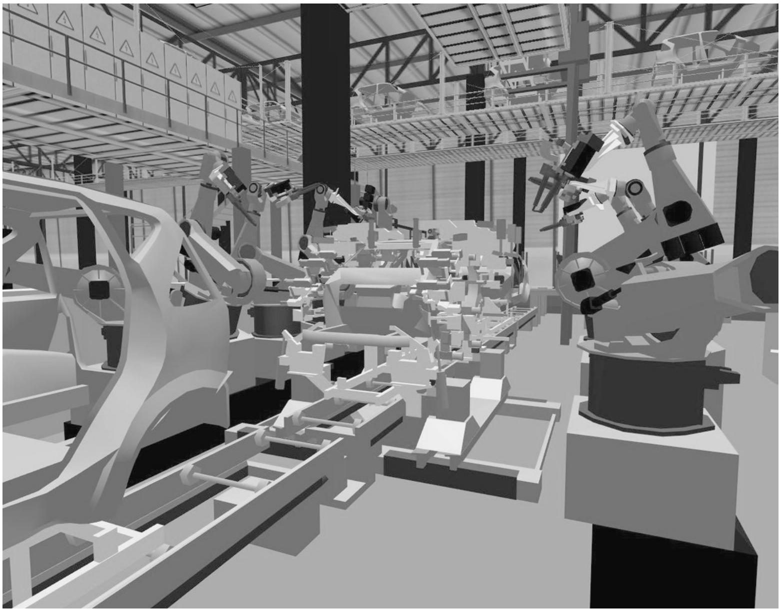

Figure 7 Robot Welding Cell of a Production System. (*Source:* HLRS and Fraunhofer IPA)

- *Application level:* advanced

The immersive visualization of production and workflow simulations greatly increases the clearness of the production cycles and helps to identify problem areas quickly. Therefore, a large field of view is essential. The ideal IPT system used here is a CAVE-like multiwall projection system. Currently, most of these applications are used for presentation purposes only. Offline teaching of robots in VR poses a number of problems, most involving accuracy and usability.

5.3. Education and Training

By means of virtual environments a learning context can be created where the multiple aspects of human intelligence are addressed. With sufficient perception and interaction qualities to give the learner a feeling of intuitive handling of virtual objects to the learner, the following VE applications are possible in the area of apprenticeship.

- Interactive demonstration of objects and events
- Mediation of (abstract) knowledge based on the user's experience (e.g., exploring a molecular structure)
- Mediation of skills and training of behavior in dangerous situations and environments
- Knowledge mediation beyond humans physical limitations (e.g., exploring how a gasoline engine functions by opening up the combustion chamber)
- Exploring distant places or past epochs
- Advancement of creative abilities by free design and impart of imagined objects

The use of VE systems in teaching, education, and training can be very effective because it agrees with the psychological and pedagogical knowledge, which is that the greatest success in learning can result from the practical application of educational programs and case studies. The success of learning can be increased by parallel addressing which means frequently changing the sensory channels, and by the inclusion of the learner's own actions. Concentration and learning success increase when thinking structures are fixed in the imagination or the ideas of a third person are made intelligible.

Particularly in the artistic field, VE should contribute to supporting students' creativity. In addition to this, when VE is is used in language education, the simulation of a suitable environment will make the learning of a foreign language more intensive and therefore more effective.

5.4. Scientific Visualization

The 3D representation of complex data is applied to the examination of comprehensive geometry data records and, especially in the scientific visualization field, the representation of mathematically computed data. The visualization of mathematically computed data has the goal of rendering simulation results visible, audible, or tactile.

6. PROCESS INTEGRATION OF VR APPLICATIONS

VE must be integrated in the development process with respect to the available 3D geometry database, the communication structure between departments, and the specific characteristics of the product.

The use of VE-based tools in a virtual immersive work environment with real-time capability speeds up finding and reviewing concepts in the early stages of the development process. Product aspects and features of prototypes can be examined in the virtual environment that so far have been verifiable only in real, physical prototypes (Figure 8). For this purpose, product aspects and features can be represented directly or indirectly by means of metaphors. In a passenger car, for example, the shape and the room required by individual units are directly presentable product aspect and features, in contrast to the dynamic load of the chassis (which is indirectly presentable by means of metaphors). Connecting these steps in the early development with quality, time, and cost management will create several advantages.

6.1. Analyzing Engineering Tasks for VE Applications

The field of engineering, apart from planning tasks, above all handles complex contents of engineering and the natural sciences, which will be discussed in the global engineering network on the basis of CSCW in the future. Unlike planning tasks, engineering and the natural sciences can in many cases not be discussed exclusively on the basis of numerical values or texts. Frequently they involve complex, multidimensional problem scopes. Therefore, a discussion of these subjects is supported by a spatial, multidimensional representation of the contents.

The major weak point of the computer-assisted simulation and design tools that have been available so far is that ideas of 3D geometry and/or functions are handled by 2D input/output media. This disadvantage is intensified by the growing complexity and multidimensionality of the problem at hand. A thoroughly interdisciplinary discussion of the scope of the problem is hampered by the existing tools, which are usually very specialized, whereas the multisensory and immersive systems of virtual reality (VR) support quick and interdisciplinary visualization of contents.

The use of conventional computer systems in such complex processes as the design of product shapes or the evaluation of assembly processes requires the user to have a great ability to think in abstract terms. To provide more intuitive access to these problem scopes, the problems can be handled in a VE.

Virtual prototypes (VP) are defined as a computer-based simulation of a technical system or subsystem with a degree of functional behavior which is comparable to corresponding physical pro-

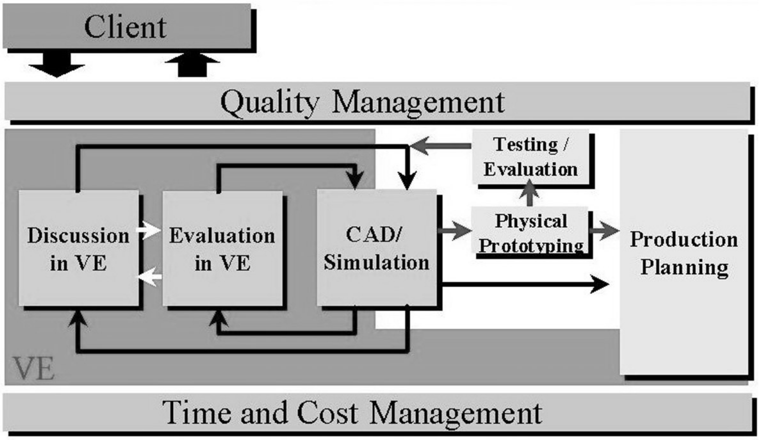

Figure 8 Use of VE in the Development Process.

totypes (Haug et al. 1993). Practically speaking, VP is a 3D graphical representation of an object that can be manipulated in its geometry, surface, behavior, and other degrees of freedom in real time. The source of the information can be parts from the traditional design process, such as hand-made models and drawings that are digitized in all their features, such as by 3D laser scanners with videocapture capabilities for catching surface information. Another option is the use of digital databases, which can store nearly everything from CAD files on materials and colors up to rules and standards for the generation of a new virtual prototype. Because all the data used inside the virtual prototype are digital, changes to the virtual prototype can be reflected quickly in the digital model without physical effort. This same model can be used in different ways to get feedback on various aspects of the design and its performance.

Are there any specific characteristics of the tasks that guarantee a maximum benefit when using immersive VR systems, or rather an IPT system? If we analyze engineering tasks focusing on the use of immersive projection environments, we should do so with regard to aspects of the following areas:

1. Representation of the product (model, prototype) and the user
2. Communication between users about the engineering task
3. The Engineering task itself

In addition, we have to check our requirements for costs, quality, and time. For costs, key words are investment, the costs for physical models, the assessment of earlier time-to-market, decision support through more realistic models, and checking of customer acceptance of reduction of risks. The quality can be enhanced through more variants (digital mock-ups), the integration of implicit know-how (as well as experience) by assessing the digital models, and the reduction of bugs early in the development process. This can also be a relevant factor in shortening the time of the whole development process, in addition to there being fewer real prototypes necessary and the digital manufacturing process needing less time to achieve the final quality of the series.

Most tasks can be done by transferring the tasks in immersive VR systems. Therefore, the user can choose different IPT systems based on the tables above. But each task has its own specific characteristics and has its specific benefits. Below are some typical tasks based on examples and experiences regarding benefits:

- Visual evaluation of the form
- Visual evaluation of the position of different parts
- Visual evaluation of proportions
- Assessment of surface quality
- Evaluation of color concepts
- Evaluation of colors
- Modification of geometry
- Modification of colors/textures/material appearance

TABLE 1 Ranking of IPT Task Requirements

		CAVE-Like	Power Wall	Benches	HMD	HCD
Scale	micro	+	0	+	+	+
	1:1	++	+	0	+	+
	macro	++	++	−	+	+
Simulation of human activities by the user		++	0	0	+	−
Immersion of the user in the VE		++	+	−−	+	+
Immersion of the user in the product		++	0	−−	+	+

−−: not possible
−: not suitable
0: possible
+: suitable
++ : very suitable

- Assessment of kinematics
- Auditory evaluation

Tasks that allow visual spatial perception for a subjective assessment of product characteristics are especially convenient for the use of immersive projection environments. Tasks with high complexity (especially in spatial aspects) that have to be discussed in an interdisciplinary team also have interesting advantages for using VR.

Because we use visual perception especially in immersive projection technology (IPT), we have to ask which product characteristics we can assess there. The product characteristics for which we can achieve reliable assessment differ between the real world and a virtual environment. Therefore, Table 2 ranks characteristics and their relative usefulness for direct representation and assessment in the different IPT systems.

The goal of digital mock-ups is the assessment of products early stage in the development process. For direct assessment, the digital mock-up should have nearly the same characteristics as the final product. But if we think only in such a direct way of assessment we get only a small part of the possibilities and advantages of digital mock-ups. As in other fields of science and technology, we have to learn to think of assessment in an indirect way. That means that it is not possible to measure or assess a specific parameter or characteristic of the product, but it is possible to measure or assess a number of other parameters or characteristics from which we can derive the specific characteristic. With the less useful ranked characteristics in Table 1 we should try this strategy of substitution or indirect assessment. Therefore, we have to look for adequate metaphors.

6.2. Requirements from the Engineering Side

For a quick development process, the definition of geometry must be, in principle, closely linked to the evaluation of particular product features that are influenced through geometry. For this reason, design and evaluation form iteration loops that reach a higher level of design of the prototype after each iteration step. The tools necessary for executing of the described tasks in the virtual environment are being researched, conceived, and developed within the scope of the subproject. In addition to the tools for design and evaluation, communication and cooperation in the virtual environment are primary requirements. Within this subproject, the fundamentals of the representation of the actor are researched. The representation model, which is based on the above-mentioned fundamentals, is integrated into the virtual working environment. The tools for design and evaluation are the basis for an interdisciplinary project by experts on the basis of CSCW in a virtual working environment. A user guidance system adapted to this environment has to be developed for system control.

The advantages of VE are:

- 1:1 scale
- Immersion

TABLE 2 Ranking of Product Characteristics with Respect to Representation in IPT

		CAVE-Like	Power Wall	Benches	HMD[a]	HCD
Geometry	Form	++	+	+	+	+
	Continuity of the surface	+	+	++	+	+
	Proportion	++	+	0	0	0
Material	Color	0	0	0	+	++
	Surface structure		+	0	+	++
	Haptic characteristics	−−	−−	−−	0[b]	0[b]
Kinematics		++	+	+	+	+
Acoustics		++	+	+	+	+
Functionality	User interface	+[c]	0[c]	0[c]	−	−−
	Physical effects	−	−	−	+[d]	0[d]

−−: not possible
−: not suitable
0: possible
+: suitable
++: very suitable

[a] Especially LCD-based HMD in comparison to CRT-based BOOM/PUSH.

[b] In combination with a force feedback device (i.e., PHANTOM).

[c] In an augmented reality environment.

[d] In combination with special systems for physical effects (i.e., temperature device).

- Interactivity
- Intuitiveness

3D visualization from the individual line of sight and the most varied interaction possibilities through gestures, speech input, and new input/output media are still to be developed. As a result of the free positioning and scaling of the user inside and outside the object to be planned, it will be possible for a large number of persons to work simultaneously on an object. The object will not have to be broken down into its elements.

Taking advantage of a new process chain the whole process of product development and product improvement can benefit, like other fields of work, from VE-based tools:

- Reduction of cost and time for building prototypes, making it possible to test and evaluate more variants,
- Faster testing and evaluation through virtual testbeds
- Scalable test persons
- Online changes of parameters
- Enhancement of quality and effectiveness of project drawing and design performance
- Improvement of the product quality, e.g., by integrating the customer earlier and getting better feedback from the customer
- Better ecological balance through saving resources during iteration cycles

6.3. Data Requirements

3D CAD data consist of continuous area and volume description and can therefore not be used directly as a VR database. The data have to be transformed in a polygonal database by a process called tessellation. For most of the current proprietary CAD formats there are one or more data filters, called tessellators, that can also be used for generic formats such as IGES, VDA-FS, and STEP. But the best way in general is as close as possible to the generated data from CAD or other modeling tools.

Aspects of the VR database include:

- *Geometry:* continuous (CAD, STEP, IGES, etc.), discrete (polygons, voxels, STL, VRML, etc.)
- *Surfaces:* textures, reflection properties, acoustic properties
- *Kinematics*
- *Material properties*

The most important guideline for tessellation is variation of the chordal height. This value indicates the maximum permissible variation of polygon data from CAD data. However, this guideline does not fix the tessellation. There are many tessellation algorithms that can guarantee such a maximum variation. From a VR point of view, the quality assessment of the data produced concentrates on the following criteria:

- The number and kind of the produced polygons are directly linked with the frame rates achieved by visualization.
- The maintenance of the topology of CAD objects guarantees the avoidance of cracks and other inconsistencies in the VR database.
- Only the indication of correct normals in every point of polygon representation enables the correct assessment of the tessellated surface.

Most tessellators are applications within the CAD system and not independent data filters on the demand line. The reasons are as follows:

- Some relevant information is stored in proprietary CAD data only as a reference in library data of the CAD system. The tessellator must have access to these data.
- The same CAD systems on different basic programs may produce different data with the same geometric information (e.g., codepage problem with CATIA)

Tessellators of generic data formats such as IGES and VDA-FS can work on a stand-alone basis because all necessary information is contained in these data.

6.3.1. Partitioning of VR-Data Preparation

The preparation of the database (especially the 3D Geometry-inclusive attributes for surfaces, kinematics, etc.) should be distributed to the departments where the data are generated. This means that every user of the IPT system is responsible for its own VR data. The know-how for generating VR data must first be taught.

Usually there are several strategies for generating VR data, and a compromise should be made regarding the visual quality (degree of detail of the objects) and the performance of the application. This decision could best be optimized by the users who are responsible for the results.

Apart from pure geometrical information (points, polygons, normals) detailed surface information such as color, material (in the understanding of VR), and texture are needed in order to visualize CAD data close to reality. Many CAD systems already offer the possibility of defining such properties in a CAD record. However, in construction this is often ignored. The evaluation of such information, if available, is not carried through by every tesselator.

6.3.2. Material: Color, Textures

To deposit geometric data with color and material qualities is not a difficult problem and can be automated if the parameters are known. Because with every CAD construction the material in use is determined, it would be relatively simple to construct a valid databank that can link VR material qualities with material or equipment. The information needed could then be extracted from this databank, in principle. The challenge is integration in a PDM system. Therefore, the data structure of the VR objects should be designed to be flexible and modular.

The use of textures offers the possibility of reproducing surface qualities such as roughness in a VR system. How far this process can be automated must be examined. Probably it does not make sense to replace CAD geometry as low LOD stage by textures.

6.3.3. Performance Optimization

There are several aspects of performance optimization. In the construction process the tessellation of the CAD data is one example. The number of polygons produced determines the speed of real-time visualization. The finer the tessellation, the worse the graphic performance.

One problem in controlling the complexity is the goal in tessellating. In general, it is not possible to set the number of polygons that have to be produced (= complexity of VR databases) in advance but a quality criterion, namely the variation of the chordal height, is set in advance. This is ideal from the user's point of view. The estimation of a resulting polygon number from only the variation of the chordal height is extremely unreliable. In order to use the complexity as a line function, the tessellator has to be iterated until the desired complexity is reached.

However, the tessellation algorithm used has an even stronger influence on the complexity than the variation of the chordal height. If one follows the argument of the developers of OpenGL Optimizer (SGI), huge differences in complexity of the variation of the chordal height are possible. It is therefore not unrealistic to minimize the database to 20% by determining the CAD topology and total analysis of CAD surfaces. The challenge here is also integration in a PDM system where different models for high-end IPTs, desktop visualization, video-based animation, printing quality, and so on can be managed.

6.3.4. The Training Concept

It is well known that CAD requires a great deal of training, especially 3D CAD. Although the functionality of the current IPT-based tools is less complex, their handling must be taught.

Table 3 gives a brief overview of the migration from existing applications. Because a migration strategy depends very strongly on the available products, we show here only a very abstract version of migration.

7. CONCLUSIONS

The development of products mainly will base on virtual prototypes in future. Many of the virtual prototype characteristics can only be evaluated in a VE, which can provide developer or customer with an adequate perception. Changes to the virtual prototype can be quickly reflected in the digital model without physical effort—a great advantage for the engineering process. This same model can be used in different ways to get feedback on various aspects of the design and its performance. VE-based tools are being used as a vehicle for clear communication and understanding, such as in seeing how assemblies will fit together without a real physical prototype.

Immersive projection technology (IPT) is ready for productive applications. Despite the complexity of such systems, it is possible to provide them as a productive tool. Analysis and understanding of the special requirements is necessary to deliver the most appropriate system. An intuitive user

TABLE 3 Migration of Data from Existing Model

Type of Application	Type of Data	Migration
3D CAD/modeler	Free-form surfaces, parametric geometry, trim curves, surface/material properties, assembly information	Tessellation (static dynamic), data reduction (LOD), surface properties −> textures, materials, reflection mapping
Prototypes	3D scanning data sets, surface reconstruction −> CAD data sets	Data repair, data reduction, color information −> texture
Simulation (FEM/GEM, etc.)	Geometry, additional simulation data, temporal changes	Geometrical representation of simulation data, intelligent structures
Functionality	Interaction human–model, operating/behavior	Description language, feedback, intuitive user interaction

interface is very important for user productivity and acceptance. The design of 3D user interfaces is clearly progressing, at least special-purpose user interfaces created for very specific tasks. This, together with careful VR workplace design, is dramatically increasing user productivity and acceptance.

While the return on investment can be calculated immediately in some cases, in other cases will only see some excited engineers playing with the new technology.

Migration and integration of IPT and VE in standard engineering processes is a part of the second principal stream. This includes plug-ins for established VR software as well as the support of data transfer and translation of data from legacy applications. This work will depend on available standards. On the other hand, there will be a trend toward the integration of VR functionality into existing CAD/CAE packages.

All innovative media of the future will contain three major components: interactivity, co-operation, and new possibilities in receiving experience by including several senses at once. The further development of virtual reality (and all technologies included under it, such as IPT systems) must be carried out on the basis of an user-centered approach—that is, the problems and limits of a person working in an immersive VE must be considered. This is how the necessary user acceptance can be achieved.

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