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Assessment of VR Technology and its Applications to Engineering Problems

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Assessment of VR Technology and its Applications to Engineering Problems

Abstract
Virtual reality applications are making valuable contributions to the field of product realization. This paper presents an assessment of the hardware and software capabilities of VR technology needed to support a meaningful integration of VR applications in the product life cycle analysis. Several examples of VR applications for the various stages of the product life cycle engineering are presented as case studies. These case studies describe research results, fielded systems, technical issues, and implementation issues in the areas of virtual design, virtual manufacturing, virtual assembly, engineering analysis, visualization of analysis results, and collaborative virtual environments. Current issues and problems related to the creation, use, and implementation of virtual environments for engineering design, analysis, and manufacturing are also discussed.

Disciplines
Mechanical Engineering

Comments
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Virtual reality applications are making valuable contributions to the field of product realization. This paper presents an assessment of the hardware and software capabilities of VR technology needed to support a meaningful integration of VR applications in the product life cycle analysis. Several examples of VR applications for the various stages of the product life cycle engineering are presented as case studies. These case studies describe research results, fielded systems, technical issues, and implementation issues in the areas of virtual design, virtual manufacturing, virtual assembly, engineering analysis, visualization of analysis results, and collaborative virtual environments. Current issues and problems related to the creation, use, and implementation of virtual environments for engineering design, analysis, and manufacturing are also discussed.

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1 Virtual Reality Technology

Virtual Reality (VR) is often regarded as an extension of three-dimensional computer graphics with advanced input and output devices. In reality, VR is a completely new way of presenting information to the user and obtaining input from the user. The key elements of this technology are: a) immersion in a 3D environment through stereoscopic viewing, b) a sense of presence in the environment through tracking of the user and often representing the user in the environment, c) presentation of information to senses other than vision (audio, haptic, etc.), and d) realistic behavior of all objects in the virtual environment. Advanced hardware and software technologies have come together to allow the creation of successful VR applications.

1.1 VR Hardware. The traditional desktop human-computer interface consists of the monitor, mouse, and keyboard. Virtual reality technology allows for a more natural interaction with computers. This interaction is achieved by allowing a person to use natural motions and actions (e.g., pointing, grabbing, walking, etc.), which provide input to the computer. The computer provides a true three-dimensional graphics display to the user for realism and a sense of presence in the computer-generated environment. This level of interaction is achieved through a combination of specialized hardware devices and supporting software. Figure 1 shows a typical VR setup using a head-mounted display, tracking devices, and a pair of gloves.

1.1.1 Position Trackers and Body Trackers. Position trackers are sensors that are used to obtain the physical location and orientation of an object in order to map that object’s relative position accurately in the virtual environment. Very often, these sensors are attached to the human to track the motions of the person. These sensors transmit the three-dimensional position and orientation of the user in the world coordinate frame. This information is processed by the virtual reality computer program and is used to control various aspects of the virtual environment. For example, a position tracker attached to a person’s head will record the location and orientation and allow the visual display of the virtual environment to be updated correspondingly. Thus, in order to move forward in the virtual environment, the user simply steps forward. Position trackers are frequently used for three purposes: a) to track the human in the environment, b) to allow objects to be moved in the environment, and c) to provide additional tools for human-computer interaction.

The primary technologies used for tracking are: electromagnetic, acoustic, mechanical, optical, inertial, and imaging technology. Of these methods, electromagnetic tracking is by far the most popular. These devices are relatively inexpensive and small in size. The tracking data obtained from these devices is very repeatable. However, there is significant distortion of data if there are metallic objects present nearby. This leads to a significant amount of time spent in calibrating the environment [1,2]. Acoustic tracking devices are also inexpensive but do not have the range and accuracy provided by electromagnetic trackers. They are also very sensitive to acoustic noise in the environment. Mechanical tracking devices use encoders and kinematic mechanisms to provide very fast and accurate tracking. But these devices are not very
practical in fully immersive applications because of their limited range of motion and physical size. Optical trackers are very accurate and typically consist of emitters (LEDs, etc.) and receivers (cameras) mounted in the environment and on the user. The problems with these devices relate to occlusion because of the user’s movements and the cost of creating special rooms to support these devices. Inertial devices have recently become popular and there are some devices available now, which combine inertial techniques with acoustic and magnetic compass devices. These devices suffer from drift and size problems [2]. Imaging using video cameras is a recent technology and needs to mature significantly to warrant serious consideration in engineering applications.

Body tracking through the use of tracking devices is a complex process and several devices have been created specifically for body tracking. For example, several products from Ascension Technologies are aimed at supporting multiple trackers attached to various parts of the human body for full body tracking. Table 1 lists several currently available commercial tracking devices and some of their capabilities.

1.1.2 Stereo Display Devices. Stereoscopic display is the second key element that gives the user a sense of presence in the virtual environment. Stereo viewing is provided primarily by two technologies: stereo-glasses and head-mounted displays (HMD). Stereo-glasses are worn just like regular glasses and provide a stereo view of the computer data. There are two main types of stereo-glasses: (1) passive stereovision, and (2) active stereovision. In active stereovision the two images required for stereoscopic vision are displayed sequentially on a monitor or a projection screen. The LCD panels on the shutter glasses are synchronized with the display screen to allow viewing only through either the left eye or the right eye. In passive stereo the left and right eye images are polarized on the screen and the user wears polarized glasses. Stereovision glasses are used with monitors or with large projection screens. Projection systems can be made up of a single large projection screen or several projection screens arranged as a room, commonly called a CAVE. Some companies (e.g. TAN Projektionstechnologie) supply systems with cylindrical viewing spaces. These systems provide a large field of view and allow multiple participants to collaborate in the virtual environment. The stereo glasses are coupled with position trackers to provide position information to the virtual reality program. Table 2 lists examples of projection-based stereo viewing systems.

Head-mounted displays are helmets that are worn by individual participants. Separate right-eye and left-eye views are displayed in small CRTs or LCDs that are placed in front of each eye in the helmet. Recent advances in HMD technology have resulted in commercially available HMDs, which are lighter, less expensive, and have better resolution when compared with previous models. Combined with a position tracking system, the HMDs allow participants a full 360-degree view of the virtual world. Although HMDs can be networked they are most often used by a single participant. Table 3 lists several commercially available HMDs.
1.1.3 Input Devices. Users of VR systems need methods other than the standard mouse and keyboard to provide input to the computer. Being fully immersed makes this a difficult problem. Several commonly used methods include 3D menus that float in space, voice input, joysticks, forceballs, and gloves. When 3D menus are used, the method used for selecting these menus vary from the use of a “wand” to touching the menu with a fingertip. A wand is a hand-held input device that contains several buttons. When the wand is coupled with a position tracker, the user can move the wand in the environment, press a button, and cause something to change in the computer-generated environment. The Pinch Glove™ is a glove that has electrical conducting material on each fingertip and the thumb tip. Touching any fingers and/or the thumb together completes a circuit much like a button press. The CyberGlove™ contains strain gage sensors that run along each finger and the thumb. These sensors determine the angular flexion of the fingers as the hand moves. The CyberGlove™ can be used to obtain very accurate information about the shape of the hand as the user is interacting in the virtual environment. Gestures made by a user using the CyberGlove™ are also used as input to VR applications. Point input devices include the six degree of freedom (DOF) mouse and force ball. Six DOF mouse functions like a normal mouse on the desktop but can also be lifted from the desktop to function in 3D space. An example of such a

<table>
<thead>
<tr>
<th>Software</th>
<th>Computer Platform/API</th>
<th>Distributed applications capabilities</th>
<th>Multiprocessing capabilities</th>
<th>VR hardware supported</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alice [11]</td>
<td><a href="http://www.ali">http://www.ali</a>...</td>
<td>Windows</td>
<td>Multiprocessing performed automatically</td>
<td>Limited support for VR devices: MDMs, gloves, trackers</td>
<td>Rapid prototyping VR software, easy to learn, made for non-technical users, freeware, uses either a GUI interface or the Python scripting language, development of large scale immersive applications is limited</td>
</tr>
<tr>
<td>Avocado [4,5]</td>
<td><a href="http://visvisiz">http://visvisiz</a>...</td>
<td>Silicon Graphics/IRIS Performer-based</td>
<td>Yes</td>
<td>CyberStage CAVE, the Responsive Workbench, trackers, input devices</td>
<td>Rapid prototyping tool, uses Scheme scripting language, allows run-time loading of new objects</td>
</tr>
<tr>
<td>Division Reality [13]</td>
<td><a href="http://www.ptc">http://www.ptc</a>...</td>
<td>Silicon Graphics, Sun, HP UNIX, Windows NT</td>
<td>Yes</td>
<td>Supports multiple projection-based systems, MDMs, Immersive Workbench, trackers, input devices</td>
<td>Imports CAD geometry, uses a high-level scripting interface or GUL, provides for collision detection and object behaviors, strong emphasis on product simulation</td>
</tr>
<tr>
<td>Lightning [14]</td>
<td><a href="http://www.l">http://www.l</a>...</td>
<td>Silicon Graphics/Performer-based</td>
<td>None</td>
<td>Automatically distributes to multiple processors</td>
<td>Supports multiple projection-based systems, MDMs, BOOM, trackers, input devices</td>
</tr>
<tr>
<td>MR Toolkit [12]</td>
<td><a href="http://www.cs">http://www.cs</a>...</td>
<td>HP-UNIX, SGI, IBM-UNIX, Sun, DEC Alpha, Windows (MRObects version/OpenGL or PCI-based</td>
<td>Yes</td>
<td>Supports MDMs, trackers, input devices</td>
<td>Free to academic and research institutions, applications in C, C++, or FORTRAN, no support for collision detection or multi-user applications, need to write source code in C++ or FORTRAN, includes ability to perform collision detection and object behaviors</td>
</tr>
<tr>
<td>WorldToolKit</td>
<td><a href="http://www.se8">http://www.se8</a>...</td>
<td>Silicon Graphics, Intel, Sun, HP, DEC, PowerPC, Evans and Sutherland</td>
<td>Yes</td>
<td>Supports multiple projection-based systems, MDMs, BOOM, trackers, input devices</td>
<td>Supports 3D and stereo sound, very widely used</td>
</tr>
<tr>
<td>VRJuggler [9]</td>
<td><a href="http://www.vr">http://www.vr</a>...</td>
<td>Silicon Graphics, Linux, Windows NT, Solaris, FreeBSD systems, HP-UNIX/OpenGL or Performer-based</td>
<td>Yes</td>
<td>Supports multiple projection-based systems, MDMs, BOOM, trackers, input devices</td>
<td>Ability to reconfigure, restart, or replace devices and displays at run time, VR devices are transparent to the programmer, simulator model available, no built-in support for collision detection or object behaviors, Open Source code</td>
</tr>
</tbody>
</table>

Data from Ref. [14] included in table.
device is the Flying Mouse™ from Logitech. A force ball interprets mechanical strains which result from the user applying forces and torques to a ball affixed to the tabletop. An example of such a device is the Space Ball™ from Space Ball Technology Inc. The Polhemus™ Stylus is a pencil-shaped device, which allows an accurate position tracking of the pencil tip. This input device can be very useful for user interfaces with virtual menus using physical props.

One of the most effective ways of communicating with a computer when immersed in a VR environment is through voice input. This method is rapidly gaining popularity with improvements in speech recognition technology. However these systems are still not very robust. Examples of such software are VoiceAssist™ from SoundBlaster, IN3 Voice™ from Command Corp. Inc., VoiceType™ from IBM and DragonDictate™ from Dragon System Inc.

Devices that can be used to detect eye movements (biocontrollers) can also be used as input to VR systems. Biocontrollers can process indirect activities, such as muscle movements, and produce electrical signals. Such devices are still in the testing and development stage. Limited success has been reported in applications of eye tracking to assist handicapped people. Some devices allow eye motions to control the mouse on a computer screen with blinks signaling mouse button clicks [3].

1.1.4 Audio. Stimulation of multiple human senses increases a person’s sense of presence in the virtual environment. Sound is commonly incorporated into the virtual scene to provide additional information to the user about the computer environment. Often, when an object is selected, a sound is used to confirm the selection. Sounds can also be associated with locations in a virtual environment. The virtual environment can be programmed such that as a person approaches a large manufacturing machine in a virtual factory, the sound of the machine gets louder. The addition of sounds can contribute greatly to the virtual experience of the participant.

1.1.5 Haptic Feedback. One of the major differences between interacting with objects in the real world and interacting with objects in a virtual world is in force feedback. In the real world, when a person touches a table, he/she feels a reaction force from the table. In the virtual world, users ““touch” virtual objects that don’t really exist so there are no reaction forces. Recent research into the development of haptic devices is targeted at developing this ““touch” capability. In the virtual environment, as a user moves the haptic device into an area occupied by a virtual object the device is activated and supplies reaction forces to the user.

The most popular haptic feedback device at this time is the PhanToM™. This device is a three degree-of-freedom desktop device, which provides only point contact feedback. Many medical applications have been developed to use the PhanToM™ for training surgeons. Recently engineers have started to use this device to perform free-form modification of surfaces. New six degree-of-freedom PhanToM™, which includes torque feedback, has recently become available. Successful applications reported include haptic force feedback in applications such as molecular modeling, assembly, and remote sensing.

The CyberGrasp™ is another haptic device that is commercially available. This device consists of an exoskeleton worn with a glove. The exoskeleton pulls on the fingers of the hand when the hand is in contact with virtual objects. This device is very portable and can be worn on the hand as a user is walking around the virtual environment. It is still difficult to represent grabbing shapes with this device. The user feels a force when the hand intersects virtual objects, but shape detection is difficult. Grabbing a virtual steering wheel or a virtual shift knob feels the same.

1.1.6 Computer. The computer system driving the VR application is usually a specialized computer. Most engineering applications of VR require high-performance graphics and high-speed computation capabilities. Many high-end computers (e.g. SGI Onyx) combine these capabilities for VR applications. Along with providing multiple processors and large amount of RAM, these computers also provide multi-channel graphics capabilities for the multiple viewing required for stereoscopic and multi-wall image generation. In some cases, there are multiple graphics pipes (i.e. separate graphics processing hardware pipelines) to improve the graphics performance. These systems are very expensive. Some PC-based systems are now available which support dual, synchronized graphics cards. There has also been a recent thrust in using PC clusters to address the issue of high-performance computing required for these applications.

<table>
<thead>
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<th>Table 4 (Continued)</th>
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<tr>
<td><strong>REALAX</strong></td>
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<tr>
<td><strong>Virtual Design 2</strong></td>
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<tr>
<td><strong>OptiCore Opus Studio</strong></td>
</tr>
<tr>
<td><strong>Covise</strong></td>
</tr>
<tr>
<td><strong>Ensign Gold</strong></td>
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MARCH 2001, Vol. 1 / 75
1.2 VR Software. Most of the VR applications used in engineering have been custom-developed using C or C++ software libraries. These VR libraries provide functions to read position data from the tracking systems and manage the displays, either stereo HMDs, single or multiple projection screens or other devices. Table 4 presents a listing of some virtual reality software packages available for the creation of virtual environments. Most of these are general purpose virtual reality toolkits such as Avocado [4,5], Bamboo [6], CAVE library [7], Muse [8], and VRJuggler [9]. Ensight Gold is a computer aided analysis tool with VR capabilities and is not meant as a general VR tool. Bierbaum and Just [10] identify three primary requirements for a system that supports the creation of VR applications: performance, flexibility, and ease of use. These requirements often conflict and result in the availability of many software systems each developed to satisfy different levels of these three requirements. For example, the Alice [11] software was specifically designed to be easy to use in order to provide non-programmers with a VR development tool. However, Alice is not very flexible in that it is limited to the creation of simple environments. Complicated scientific visualization applications would not be appropriate for development using Alice. On the other end of the spectrum are the more versatile programming toolkits such as VRJuggler and MR Toolkit [12]. For each of these software toolkits, a firsthand knowledge of C++ and object-oriented programming is required. The result is that there are a number of software packages on the market, each with different capabilities and features.

The decision on which software tool to select must be based on many criteria related to the application and the VR equipment. The extent of the application must be considered as well as the need for multiple participants to be involved in the application. The ease of programming and future updating of the application is also a consideration. The GUI input to Division Reality [13] makes programming and updating easy but does not allow for customization of the application. Speech recognition and 3D sound are required in some applications. Other applications require the display and interaction with a significant amount of data. Ensight Gold is especially designed to handle large computer aided analysis data sets but has limited VR hardware support and is not easily modifiable. The ease of importing data into the virtual environment is also an important consideration. Division Reality includes several CAD data converters as part of the software. If there is a need to develop several different VR applications using different hardware, then a general purpose VR software toolkit such as Avocado, Bamboo, Muse or VRJuggler would be appropriate.

2 Engineering Applications

Initial engineering applications of virtual reality concentrated on providing methods for three-dimensional input and stereoscopic viewing. However, over the past five years, several advanced applications have changed the engineers’ perspective of the product development process. These applications span from conceptual design tools to manufacturing simulation tools and maintenance assistance tools. Many of these applications have been fielded with varying degrees of success by industry. This section describes some of these applications to provide a view of the state of the art in engineering applications of VR. Table 5 lists several of the VR applications developed for product life-cycle support.

Today’s typical design process involves computer modeling followed by construction of physical prototypes to verify the digital models. Because virtual reality offers a three-dimensional design space where the user interacts with the three-dimensional computer images in a natural way, using VR technology as a prototyping tool holds great promise. For example, many more design options can be examined in a shorter time if they exist purely in digital form as compared to building and testing physical prototypes. There are many design decisions that must be made before a product enters full production. The place where virtual reality makes a significant difference in design evaluations is in evaluating the relationship of the human to the product design. Using the traditional computer interface consisting of a monitor, mouse and keyboard, users are removed from interacting with the digital product designs. Using a virtual reality interface brings the user one step closer to interacting with the digital design as if it were a real object.

2.1 Conceptual Design. Three-dimensional modeling and VR applications provide engineers with methods to evaluate virtual prototypes early in the design stage and make modifications, which result in significant cost and quality benefits. Many of the VR applications fielded today in industry assist engineers in the concept design stage. A set of examples of such applications is provided below.

In vehicle design, operator visibility and operator interaction with devices, switches, knobs, etc. are critical aspects of the product. Physical prototypes are often built so that users can interact with the vehicle to evaluate placement of these devices. The goal of virtual prototyping is to reduce the number of physical prototypes that are required by designing virtual environments, which can be used for vehicle ergonomic evaluation. An intermediate step, short of developing an immersive virtual environment is the use of computer models of articulated humans, which are programmed to interact with the digital car models. There are several software packages available on the market which provide these digital humans, e.g. JACK™, FIGURE™, DI-Guy™, SAFEWORK®, and RAMIS™. All of these digital humans are primarily simulations. Using this software, the models are displayed on the computer monitor and moving the viewpoint is accomplished by moving the mouse. Moving the joints and limbs of the human are accomplished using the mouse and keyboard. JACK™ provides limited support for the use of tracking devices in conjunction with their simulated human model. It is difficult to...
simulate a person leaning out the window of a vehicle cab and flipping a switch at the same time using these traditional devices. None of these applications allow the user the freedom to move around the digital model using natural human motions. Immersive virtual environments provide this interface. Instead of programming a virtual human, applications can be written where a human interacts with the digital models in a fully immersive application. Jayaram et al. [15–17] have developed a virtual prototyping application to perform ergonomic evaluations inside a vehicle. Figure 2 shows the application user with all the VR peripherals and the virtual human in the truck cab. This application has been used by industry to investigate reach, visibility, and comfort of a prototype vehicle design. Capabilities of this application include: automatic data translation from CAD models, fully scalable parametric human model, tools to reconfigure the interior layout in the immersive environment, reverse data transfer to the CAD system, realistic environment creation, and internet-based distribution for collaborative design reviews.

Oliver et al. [18], working with Deere and Company, placed a virtual front-end loader in an immersive virtual environment. The virtual environment allowed the user to raise and lower the front bucket and investigate the visibility from the operator’s seat as the bucket was moving (Fig. 3). This application also allowed the user to relocate a light fixture attached to the front arm of the bucket so it would not obstruct visibility during bucket operation.

Other successful virtual ergonomic applications include visibility and simulation of backhoe loaders (Caterpillar), interior design evaluation (General Motors and Ford Motor Company) [19,20], and ergonomic evaluations of vehicle interiors (Daimler-Benz).

One of the more difficult evaluations to make using digital models relates to a vehicle operator’s use of mechanisms. Mechanisms are found throughout all types of vehicles and include such devices as the shift lever, radio buttons, window visor, cup holder, parking brake and glovebox door. In the design of a vehicle, the location and operation of these mechanisms is key to the user’s comfort in the vehicle. If these design decisions (where to place the mechanism and how to make it move) can be evaluated with a user operating a digital model of the mechanism, then several alternative designs could be examined very quickly and evaluated to obtain the best design.

Volkov and Vance [21] investigated the use of a haptic device to provide constrained motion for virtual mechanisms commonly found in the interior of a vehicle. The purpose was to determine if users make the same decisions concerning the operation of a mechanism in a virtual environment with constrained motion as they would in a virtual environment without constrained motion. Two groups of participants were asked to manipulate a virtual parking brake in the interior of a virtual automobile (Fig. 4). One group used a haptic device constrained to replicate the motion of the mechanism while the other group used the haptic device as a six-degree-of-freedom input device without constraints. Initial results indicate that accuracy and precision were not significantly different between the two groups, but the group that used the haptic feedback device took considerably less time to perform the evaluations. The implications are that the addition of haptics to constrain mechanism motion does not increase a participant’s ability to judge motion and placement of the mechanism but it does allow participants to perform an evaluation in shorter time.

Spatial mechanism design can also benefit significantly through the use of virtual environments [22,23]. An immersive environment for the design of spatial mechanisms was developed by Furlong et al. [24]. This application allows the user to place positions in three-dimensional space, synthesize a spherical mechanism and examine the movement of the mechanism. Mechanism dimensions can be saved and later used to manufacture the links. Evans et al. [25] performed a study to characterize different VR user interfaces based on the spherical mechanism design application. Although most virtual prototyping applications are developed to interface with existing CAD models, several researchers are investigating the use of virtual reality for conceptual shape synthesis. Dani and Gadh [26] have created a VR-based system (called Virtual Design Studio - VDS) for the rapid creation, editing, and visualization of complex shapes. As opposed to the WIMP (Windows-Icons-menu-Pointer) paradigm, common to most current CAD systems, the VDS system is based on the WorkSpace-Instance-Speech-Locator (WISL) approach [27]. In this system, the designer creates three-dimensional product shapes.
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by voice commands, hand motions, and finger motions, and grasps and edits features with his/her hand motions. Designers can rapidly configure shapes in VDS by allowing higher-level creation and editing of feature representations of the geometry [26]. Exact geometry models are generated and analyzed in VDS using the ACIS geometry kernel. A comparative study on shape creation in different CAD systems showed that geometry can be created in the VDS system using only half of the conventional design steps, achieving a productivity of 10-30 times over conventional CAD systems [28]. In this scenario, the interface interaction mechanisms of the VR-CAD system play a very important role with respect to efficiency, intuitiveness, and accuracy [29].

2.2 Preliminary Design and Design Analysis. Preliminary design is often the stage where the shapes and sizes of objects are optimized based on analysis. Virtual reality presents a unique interface for interpreting analysis data. Virtual reality can be used as a general post-processing tool for commercial finite element analysis (FEA) codes. The first ever VR application in engineering was the “Virtual Wind Tunnel” created at NASA Ames [30]. Ryken and Vance [31] and Yeh and Vance [32] present a virtual environment for the evaluation of results from a finite element analysis application. In addition to investigating stress contours, the application provides the ability to change the shape of the part and examine the resultant changes in the stresses (Fig. 5). Using this tool, analysts can interactively determine where to change the shape to reduce stresses before attempting a complete finite element analysis. Using a combination of NURBS geometric modeling techniques and finite element sensitivities [33-34], the user can reach into the virtual environment, change the shape of a product and interactively examine the changes to the stresses in the product [35,36]. Once a suitable design has been achieved, the complete finite element analysis is performed to obtain the actual stresses. This technique has been successfully applied to the design of a lift arm for the three-point hitch on a tractor [37]. Stresses on the underside of the lift arm in the yoke area were extremely high. By interactively changing the shape of the arm in the virtual environment, a new satisfactory solution was obtained.

Shahnavaz et al. [38] have developed a similar virtual CFD post processing tool that uses the C2 virtual environment. Similar to the FEA example described above, the CFD results and geometry are read into the virtual reality program. In the environment, users have the ability to place cutting planes, streamlines, and rakes. Several available scalars can be color mapped onto these entities. In addition, iso-surfaces and full field velocity vectors can be displayed. Velocity components can be shown on a cutting plane. All of these entities are displayed in real time. As the user moves the wand in the environment, the streamline or cutting plane attached to the wand is updated in real time. Thus, the user can move around the environment and interactively investigate the fluid flow characteristics.

Current CFD analysis programs are capable of analyzing and predicting very complicated three-dimensional flow fields. While these fields can be shown on the computer screen, the ability to walk around the data and place entities easily in the three-dimensional space helps increase our knowledge and understanding of the flow fields significantly.

Other examples of data visualization and data representation using VR environments include force display of interaction forces in MEMS assembly [39], flow field visualization for automotive applications [40], crash analysis [41], and CFD simulations for room layout designs [42].

2.3 Manufacturing Planning. Another very promising application of virtual reality is in the area of virtual assembly, disassembly and maintenance. Once again the focus is on reducing the number of physical prototypes required by providing a virtual environment for evaluation of digital models. Often, in product design, most of the geometry of the product is finalized without evaluation of the assembly process required to manufacture the product. However, ineffective assembly methods are very expensive in the long run. Virtual assembly methods prototyping provides a means for production engineers to participate early in the design process where design changes are less costly. This will lead to products which can be efficiently maintained, reused, recycled and assembled [42,43].

There are traditional computer applications that perform assembly using the monitor, mouse and keyboard. Some examples of such systems include products from Delmia, Tecnomatix, EAI (Unigraphics), etc. Virtual humans can also provide information on ergonomic aspects of the assembly operation. But where virtual reality has added benefit is in determining the relationship between the assembly operator and the parts. Virtual environments allow users to move around and assemble the parts of the assembly as if they were on the assembly line. Ergonomic evaluation of the assembly task can be determined by examining real users manipulate virtual models instead of programming virtual humans to perform the tasks. Also, assembly process changes (such as tool changes, sequence changes, etc.) can be naturally tried out by the assembler in the virtual environment without any need to reprogram the human model or the simulation system.

Jayaram et al. [42,44-48] have developed a virtual assembly application called VADE (Virtual Assembly Design Environment) in a partnership with the US National Institute of Standards and Technology (NIST). VADE is an advanced tool for immersive evaluation and planning of assembly processes. Methods have been created to automatically transfer CAD models of assemblies, sub-assemblies, and parts to the VADE environment. The data translated includes geometry, mass properties, inertia properties, assembly hierarchy, and assembly constraints. In the immersive environment, the user can perform two handed assembly evaluations by picking up the base part with one tracked hand and picking up other parts with a gloved hand. The process of grabbing and manipulating parts is based on the physics of gripping (Fig. 6). The geometry constraints used to assemble the parts in the CAD system are extracted and used in the immersive environment to guide the user (Fig. 6). This helps preserve the assembly design intent between design and manufacturing.

Part motion in VADE is driven by the combined dynamics of the user’s hand, gravity, and collision with other objects. The dynamics calculations are done in real-time (Fig. 7). VADE capabilities also include collision detection, creation and editing of swept volumes (Fig. 8), parametric design modifications in the immersive environment with automatic data transfer back to the CAD system, tools and jigs, and a realistic environment. VADE
has been used successfully in several studies using models from
the truck, engine, machine tools, and construction equipment
industries.

Srinivasan and Gadh [49] developed The Assembly Disassembly
in Three Dimensions (A3D), which focuses on digital pre-
assembly analysis. This involves generating, editing, validating
and animating assembly/disassembly sequences, paths, and cost/
time for 3D geometric models. A3D maintains a hierarchical as-
sembly structure and allows the user to add constraints, edit the
overall component shape, and compute the resultant sequence,
paths and cost/time in a virtual environment. In a semi-automated
fashion, the user can generate complex sequences and paths of
components and validate the resultant assembling/disassembling
operation. In addition, the user can perform several other virtual
manufacturing analyses such as interference checking, clearance
checking, accessibility analysis of components, and design rule
checking. A3D is built using both ACIS and PARASOLID geom-
etry kernels. A3D can analyze assembly models in PARASOLID,
SAT, IGES, SAT, STL, DXF, OBJ and VRML formats.

To facilitate virtual maintenance analysis, efficient algorithms
for selective disassembly of one or more components were devel-
oped and incorporated in the A3D system [49,50]. The designer
may also perform design changes to facilitate ease-of-disassembly
operation using A3D.

Other work in the area of virtual assembly includes virtual dis-
assembly for product life cycle analysis [53] and virtual assembly
at BMW [54].

2.4 Factory Layout. Closely related to virtual assembly ap-
lications are factory layout virtual environments. Because digital
models can be displayed in real size in the virtual environment,
virtual factory layout can be used to examine space requirements
for workers and products in the factory. Current traditional factory
layout applications are limited to displaying scaled versions of the
factory on a computer monitor. With virtual reality, the factory
products and machines can be placed in real size in the virtual
factory. Workers can enter the virtual factory, manipulate virtual
products, and evaluate the layout of the work cell.

Taylor et al. [55] with support from Komatsu Corporation (Ja-
pan) have created a virtual assembly application specifically
aimed at the simulation and planning of assembly of large and
heavy equipment. This application is based on the VADE appli-
cation described earlier. However, several key functionalities
needed to be added to provide an environment, which was realis-
tic enough for industry use in evaluating assembly processes for
equipment too heavy for people to lift. This environment includes
a crane and a realistic factory floor layout along with all the other
features of VADE. Special physically based modeling techniques
have been used to model the motion of parts swinging from a
 crane hook and the interaction of humans with these swinging
parts (e.g. a worker pushing a part to turn it while the part is
hanging from a crane and swinging). Figure 10 (inset) shows a
worker with the VR peripherals and the realistic crane control
box. Figure 10 shows the worker using the virtual environment
and manipulating the crane using a button box designed to simu-
late the control box used by workers in the real factory. The
environment was created using the floor plan and texture maps of
the factory walls. The factory layout is flexible and easily modi-
ifiable (creating a new, realistic, texture-mapped factory layout for

Fig. 6 Gripping a part and assembly constraints

Fig. 7 A part swinging and sliding on a shaft using dynamics

Fig. 8 Swept volume creation in VADE (Movie 3)

Fig. 9 Disassembly of aircraft engine for virtual maintenance

Journal of Computing and Information Science in Engineering

MARCH 2001, Vol. 1 / 79
evaluation takes only a few hours). The crane model is fully parametric allowing the easy creation of different types of cranes with different capabilities and physical characteristics. This environment can be used to plan the assembly process, train assembly operators, perform ergonomics studies, plan the assembly process to be used in a customer’s location, design assembly jigs, plan the layout and flow of parts and subassemblies, etc.

Kesavadas and Erzner [56] have developed a virtual factory layout program. This program called VR-Fact! can be used to model an existing factory floor or develop a new factory layout. This program incorporates the use of cellular manufacturing techniques to guide the design of the factory layout. By examining processing similarities of part groups, machines can be located in machining cells to optimize the part flow through the factory. Different algorithms can be investigated in the virtual environment and the effects of various machine layouts can be examined.

Kelsick and Vance [57] developed a virtual environment to interface with data output from a discrete event-modeling program. In this project an actual factory workcell was modeled to create the virtual environment. Actual data on part flow through the workcell was also obtained through observation of the factory operation and input into the modeling program. This virtual environment allowed the user to examine all the parts as they flowed through the factory within a given time period. Other simulations could be examined interactively. This tool allowed the user to examine many different options in factory layout and determine the effect these options had on part throughput.

Other applications in the field of factory simulation in VR environments include layout decision making [58] and simulation of a bicycle-manufacturing factory [59].

3 Hardware Technology Issues and Challenges

The examples of engineering applications of VR presented in the previous section show the current success and potential for future success of these applications. However, the fidelity and capabilities of VR and its applications are dictated significantly by the peripheral hardware and driving software. VR relies on the tracking devices for accurate positioning and fast tracking of the human, the display devices for a high-fidelity, stereoscopic, immersive graphics display, and haptics devices for the “touch and feel” in the environment. In this section some of the key issues and challenges related to these hardware devices are addressed.

3.1 Tracking Systems. Almost all current tracking devices tether the user to the control boxes with cables. Thus, if a user’s arms, legs, head and body are tracked, there are at least six cables entwining the user who is unaware of the cables once inside the helmet. There are several wireless tracking devices available at this time, but the cost is too prohibitive for widespread engineering use. The rate of data collection is typically limited in most of these tracking devices by serial port speeds and the serial processing of data. This forces the user to move slowly in the environment to have a smooth visual feedback. A significant challenge in creating these applications is in finding the trade-off between graphics lag, tracking lag, and choppy movement. Most users prefer choppy movement over smooth movement with large lag. Smooth motions with a lag between the physical movement and the display movement often lead to motion sickness.

In the near future, significant improvements are expected in the inertial tracking devices, especially with advances in MEMS technology. Wireless tracking needs to become less expensive and automatic calibration systems are needed for electromagnetic trackers. These advances will significantly advance VR technology from the point of view of engineering acceptance and use. Some of the key technical challenges in tracking devices are accuracy and reduced calibration requirements, increased data rates (~1000 Hz), wireless devices, size reduction, and ease and accuracy of attachment to a person or object.

3.2 Display Systems. The choice of a display device for a certain application should take into account the characteristics of each device. The HMD is generally a single person device and the images can be seen only in the helmet. It is difficult to write on an actual clipboard and take notes while using an HMD. In addition, the limited field of view of the HMD gives users the feeling of looking down a tunnel. Wearing an HMD for an extended period of time can cause fatigue because of the weight of the device worn on the user’s head.

The CAVE devices allow multiple participants to inhabit the virtual environment. Users can see the virtual images and also real objects that are brought into the CAVE. One of the limitations of
this technology though is the lack of ability to track multiple users. The most common configuration is where one person wears position-tracked stereo glasses and the other participants view the same image on the projection walls. This results in some viewing distortion for non-tracked users especially when working in close range with virtual objects. This inhibits communication between two people if they have to point to some virtual object, because each person will point to a different area on the screen based on their view of the environment. There are solutions commercially available today that will track two users but not more than two.

Another difficulty that arises in the use of a CAVE is that the real person can block the view of the virtual objects. Although it appears that the objects are three-dimensional because of the stereo viewing, the objects are actually being projected onto the two-dimensional projection screens. Therefore, if a user were to reach into a vase for example, the user’s hand would not disappear into the vase but it would still be visible because in the real world it is in front of the projection screen. Because of this feature, virtual representations of the hand are often used in the CAVE environment. This workaround allows the virtual hand to disappear within the virtual vase.

It is anticipated that both of these types of display devices will continue to be used for various applications. On the HMD front, increasing the resolution and the field-of-view while reducing the weight of the helmet is a big challenge. However, new devices are moving in the right direction. For the projection systems, the availability of less expensive passive stereo systems (not requiring active shutter-glasses) and brighter projectors capable of the high frequency requirements will make CAVE-type environments more viable and affordable for engineering applications.

3.3 Haptic Devices. There are several shortcomings to using the PhantOM™-type of a haptic device. For one, the device needs to be attached to a desktop. Virtual reality, because of its nature, is not a “sit at the desk” technology. Using the HMD or being in the CAVE environment, a person is most likely to stand, walk and move around in a limited area. In addition, the interface to the PhantOM™ is a pen-like device, which does not simulate grabbing real objects.

The primary issue with force feedback devices is the fact that they are mechanical devices and are bulk. To provide force feedback, the device needs to be attached to the ground to dissipate the reaction forces on bodies other than the user’s body. These limitations significantly inhibit the free usage of haptic feedback methods in engineering applications. These devices are also very cumbersome to wear. Future research in the use of these devices needs to focus on making these devices light and easy to wear. Otherwise, engineers will prefer to use audio-visual cues in the virtual environment and choose not to use haptic devices. Significant development is also required in the field of touch feedback, which allows the user to feel the surface texture, shape, and softness/hardness of objects.

4 Software Technology Issues and Challenges

The primary software issues are in the areas of: integration of VR applications with CAD systems, physically based modeling and realism in simulations, graphics and simulation speeds, and technology integration.

4.1 Integration of CAD and VR. Engineers have been using CAD systems for several decades to model and analyze their designs. CAD systems have matured significantly from the initial 2D and 2.5D systems to modern complex parametric and variational feature-based design systems. It is unlikely that VR systems will replace CAD systems as the daily tool used by designers in the near future. However, VR systems have demonstrated the usefulness of evaluating products for form, fit, function, and manufacture in a three-dimensional, realistic environment. Thus, the tight integration of CAD and VR systems is essential for the success of these applications in industry.

VR systems are still primarily extensions of computer graphics programs. The models are tessellated surface models with little or no modifiability. The tessellated models are obtained quite easily from CAD systems through VRML, Inventor, STL, and other similar file formats. However, there is significant loss of engineering data in these conversions. First, the triangulated models come nowhere close to the tolerances required for manufacturing analysis. Thus, any clearance checking performed using the display model is very superficial. Second, the number of triangles required to display realistic images is usually very large. Typical industry models of product assemblies require several million triangles for a decent visual representation. Third, the design intent in the CAD model is lost during the export to the VR system. Some applications (VADE, A3D, etc.) capture the assembly design intent and allow limited modification of design intent in the immersive application. Fourth, changes made to the product design in the VR system are often not communicated back to the master CAD model without manual data entry.

The significant challenge in this area is the creation of an underlying virtual prototyping data model for VR applications. This new data model needs to go well beyond graphics data. STEP, OPENADE [60] and other standards for product model data exchange are moving in the right direction. The goal of the OPENADE project is to identify and develop extensions to current STEP-based data formats to improve existing data transfer capabilities from traditional computer-aided design (CAD) systems to immersive engineering systems. However, the VR applications need to support all the protocols specified by these standards. Recent research done by all the authors of this paper have resulted in the reverse transfer of model modification data back to the CAD system. In one instance, the inter-feature design relationships and design intent were captured and used in the bidirectional integration of the CAD system and the VR system [15]. There needs to be an underlying philosophy of model sharing between virtual prototyping and CAD systems to address this severe data translation and data maintenance issue.

4.2 Physically-Based Modeling and Simulation. The use of VR for engineering applications automatically assumes that the fidelity of the simulation being performed is realistic and goes beyond a “video-game” simulation. Unfortunately this is not always true. There are several good, commercial, simulation products. However, these products are not designed for programming the movements of the objects and people in a simulation language and watching the results of the simulation in an immersive environment. The true power of VR is in the interactivity of the application and the changes in the system due to user participation. This requires a very high level of physically based modeling and simulation.

Physically based modeling requirements vary drastically from one application to another. The realistic interaction, collision, and bouncing of objects may be significant for assembly applications, while the realistic movement of muscle and skin tissue may be more important for ergonomic evaluation scenarios. In all cases, the equations and methods used to model the physical behavior of the environment objects are not trivial. Even after the equations are created and programmed, being able to solve these equations in real time remains a challenge. All these methods typically need to be fine-tuned to account for tracker data acquisition rates, graphics frame rates, computational capability, etc.

There is a strong need for a suite of very flexible and scaleable physically based modeling toolkits which can be plugged into VR applications at varying levels of fidelity. In the near future, we expect a number of physically based modeling and simulation methods to emerge to support realism in the virtual prototyping process.

4.3 Real-Time and Graphics. The objective of real-time simulation can be achieved by minimizing the time lag between the user-input and the VR system response. From the hardware perspective, moving towards a high-end computer is one solution.
However, from the software perspective real-time simulation of complex shapes may be achieved by adopting several techniques (e.g. level of detail switching, culling, etc.). One of the key problems associated with engineering VR applications is the fact that the complexity of the scene varies significantly as a user moves around or looks around. For example, looking out of the window of a virtual car will typically result in the display of a few polygons, which are texture-mapped to provide a realistic outside environment. As the user turns the head to look at the dashboard, the graphics now needs to display several hundreds of thousands of polygons representing the complex 3D gages, panels, etc. Thus, the graphics frame rate varies significantly causing severe inconveniences to the user. There needs to be some way of controlling the complexity of the graphics in these environments. Even if the graphics system is capable of performing at desired frame rates, the lag between user movements and responses in the simulation, the data rates coming from input and tracking devices, performing the simulation solutions in real time, and displaying the complex graphics results in a meaningful way are all challenges to be overcome.

4.4 Collaborative Engineering. Collaborative engineering and internet-based design are expected to play a major role in the changing engineering practices of the new millennium. As virtual reality tools get more accepted and used in the engineering community, the need for collaborative virtual environments for engineering applications will also increase. Several researchers have designed and created such collaborative environments. Several possible architectures for creating collaborative engineering design environments have been described [61,62]. Several prototype systems have been created which allow engineers in different geographical locations to enter and share the same virtual environment and interact with each other and with the design models. However, most of these applications are still in the prototype stage and true collaborative immersive engineering environments have not yet been fielded.

Synchronization is one of the key challenges in collaborative VR environments. The simulation and rendering speeds depend on the local hardware capabilities. This leads to situations where some of the users are “ahead” of the others in the application. Slowing down the users on the fast machines essentially leads to everyone performing at a speed dictated by the slowest system in the collaboration. Not slowing them down leads to synchronization problems with the slower systems.

Another challenge is in the integration of dissimilar systems [61]. Collaboration automatically indicates different locations, different software, and different hardware systems. The integration of data in real-time to support VR-based collaboration is key to the success of these systems.

5 System Integration

One of the most significant challenges in creating VR applications for engineering is the integration of all the technologies and tools into one coherent tool for the engineer. The requirements for the various applications and the availability of hardware and software vary so dramatically from one user to another, and from one application to another that it is not possible at this time to define a single tool as a “VR Tool for Engineering.” Each application creator needs to identify the appropriate technologies to use, design the integrated system, implement the system, test and validate the system, and train the users before the system is fielded. Some of the key issues in this system integration challenge are: integrating the new application with existing engineering applications (CAD, FEA, etc.), integrating the hardware devices with the application to provide maximum benefits to the user with minimum encumbrance, optimizing the system for performance on available computers and VR peripherals, integrating the data (input and output) of the new application with any existing PDM methods used by the user’s organization, and implementing the new process into an existing design and manufacturing process. At this time, there are no standard methods, techniques, or tools, which are available to assist application engineers in optimizing and creating a successful integration. The commercial tools available only provide tools to drive the specific hardware devices (graphics, haptics, tracking, etc.). Data exchange standards provide protocols based on CAD models and not complete virtual prototyping. In some ways, VR applications in engineering are at a point where the tools are available with instructions on how to use the individual tools, but there are no instructions on how to use the tools in a cohesive manner to create a solution.

6 Conclusions

Virtual reality technology has matured to a point where serious engineering applications have started being fielded by industry all over the world. The example applications described in this paper (and others referred to in this paper) demonstrate the sophistication of these hardware/software-integrated systems. However, not all engineering applications are well suited for immersive environments. Immersive environments provide a significant benefit to processes which require natural human motions and actions, human scale systems for ergonomic analysis, non-human scale systems to provide insight on the workings and problems associated with a product or process (e.g. viewing the workings of a MEMS device), and display of multi-dimensional data that go beyond three-dimensional graphics (e.g. using haptics to display pressures and velocities). These systems are also very valuable in reducing the number of physical prototypes required during product development by allowing virtual prototyping in true scale of the product and the process of manufacturing the product. However, there are still significant advances to be made before the engineering community embraces this technology as the next generation of computer-aided tools for design, modeling, and simulation. Some of these advances are in the area of peripheral hardware, some in the software arena, some in the integration of these systems, and some are cultural. It is not an easy task to convince engineers to give up tools they have been using for over 20 years and have them adopt a new technology. It is natural to expect that in the future all three-dimensional design and planning work will be performed in true 3D environments and not on 2D screen representations of 3D models. The shift is not expected to be overnight but more of a gradual move toward a more natural, intuitive, and capable tool that promises to bring about a revolution in engineering design, analysis, and manufacturing techniques in the new millennium.

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