Virtual Reality:
Past, Present, and Future

Enrico Gobbetti*and Riccardo Scateni†
CRS4
Center for Advanced Studies, Research
and Development in Sardinia
Cagliari, Italy ‡

Abstract

This report provides a short survey of the field of virtual reality, highlighting application domains, technological requirements, and currently available solutions. The report is organized as follows: section 1 presents the background and motivation of virtual environment research and identifies typical application domains, section 2 discusses the characteristics a virtual reality system must have in order to exploit the perceptual and spatial skills of users, section 3 surveys current input/output devices for virtual reality, section 4 surveys current software approaches to support the creation of virtual reality systems, and section 5 summarizes the report.

1 Introduction

1.1 Background and Motivation

Virtual reality (VR) is not a new concept. The origins of VR can be traced as far back at least as "The Ultimate Display" [85], a seminal paper by Ivan Sutherland that introduced the key concepts of immersion in a simulated world, and of complete sensory input and output, which are the basis of current virtual reality research. The following challenge was set:

*Enrico.Gobbetti@crs4.it
†Riccardo.Scateni@crs4.it
‡CRS4, Via N. Sauro 10, 09123 Cagliari, Italy, http://www.crs4.it

> The screen is a window through which one sees a virtual world. The challenge is to make that world look real, act real, sound real, feel real [85].

Sutherland's challenge, which can be summarized as offering presence simulation to users as an interface metaphor to a synthesized world, has become the research agenda for a growing community of researchers and industries. The motivation for such a research direction is twofold. From an evolutionary perspective, virtual reality is seen as a way to overcome limitations of standard human-computer interfaces; from a revolutionary perspective, virtual reality technology opens the door to new types of applications that exploit the possibilities offered by presence simulation.

1.1.1 Evolutionary Perspective: Better User Interfaces

The last decades have been marked by the development of the computer as a tool in almost every domain of human activity. One of the reasons for such a development was the introduction of human-friendly interfaces which have made computers easy to use and to learn. The most successful user-interface paradigm so far has been the Xerox Parc desktop metaphor popularized among computer users by the Macintosh. Graphical user interfaces based on the desktop metaphor can be seen as a limited form of virtual environment, that simplifies human-machine interaction by creating a palpable, concrete illusion for users to manipulate real, physical objects positioned on a desk top.

However, while the desktop metaphor is well suited to interacting with two dimensional worlds, it starts to show limitations when interacting with three dimensional worlds. Major drawbacks of this solution are the lack of correlation between manipulation and effect as well as the high degree of cognitive separation between users and the models they are editing [21, 33, 32]. The inadequacy of user-interfaces based on 2D input devices and 2D mindsets becomes particularly evident in applications that require users to specify complex spatial information, such as 3D modeling and animation, motion control, or surface modeling. In all these cases, the low-bandwidth communication between 2D user-interface and application, together with the restrictions in interactive 3D motion specification capabilities of the mouse, make it extremely difficult for the users to perform their work with simple intuitive actions. The feedback provided to the users is also a problem: the limited information about the structure of the three-dimensional world that is conveyed by a fixed visual image often forces the application to rely on multiple views to provide additional depth information. This requires users to combine the separate views to form a mental model of complex objects, adding further complexity to this often very difficult task [44] and forcing users to concentrate on how to obtain what they want instead of the task itself. It is increasingly evident that new device configurations and user interface metaphors that enable users to work directly in three dimensions have to be developed.

Virtual reality research, starting from the fact that human beings are well equipped to interact with the world they live in, should strive to make users interact with virtual worlds in the same way they interact with real worlds, thus making the interaction task much more natural and reducing training. The potential of virtual reality systems as a more intuitive metaphor for human-machine interaction is thus enormous, since the user can exploit his existing cognitive and motor skills for interacting with the world in a range of sensory modalities.

1.1.2 Revolutionary Perspective: Novel Applications

Virtual reality is more than just interacting with 3D worlds. By offering presence simulation to users as an interface metaphor, it allows operators to perform tasks on remote real worlds, computer generated worlds or any combination of both. The simulated world does not necessarily have to obey natural laws of behavior. Such a statement makes nearly every area of human activity a candidate for a virtual reality application. However, we can identify some application areas were benefits are more straightforward than others. The following is a summary of the most important ones.

Virtual Prototyping

Decisions taken during the design phase of large scale engineering projects are often the most delicate ones, because of their possibly dramatic effect on final results, timings, and costs. Mock-ups are routinely used for applications such as testing equipment integration, accessibility and space requirements in domains ranging from aerospace and automotive manufacturing to architecture. Virtual prototyping allows designers to test and improve their design as when using physical mock-ups, but better, earlier and with more opportunities for multi-site collaborations [5].

Architectural building walkthru have been one of the most successful applications of virtual reality. These systems, the simplest examples of virtual prototypes, permit the architect to prototype a building and to iterate with his client on the detailed desiderata for it [14, 3].

Natural interaction with digital mock-ups is very important, especially for testing purposes. In an attempt to overcome present CAD systems' interactivity and concurrent design limitations, large engineering projects have often been accompanied by the development of various kinds of specialized virtual prototyping tools [26]. Examples include the ISS VR Demonstrator used by Rolls-Royce to make an assessment of how easy it would be to build an engine and maintain it [39] and Boeing's high-performance engineering visualization system used during the design of the 777 [62]. Moreover, the

French Space Agency (CNES) and CISI have jointly launched the PROVIS [9] research project in 1995 for developing solutions for satellite designers to create, manipulate, and study their models using digital mock-ups, while CRS4 and CERN have jointly developed the i3d system for supporting the design of CERN's Large Hadron Collider [6, 7, 34, 35]. These efforts show the interest of interactive virtual prototyping for early testing of designs.

Recently, research and development efforts for building virtual prototyping systems have started independently from the need of a specific project. Ongoing research at the Fraunhofer Centre for Research in Computer Graphics is studying how to integrate existing tools to provide virtual prototyping capabilities to existing CAD systems [48]. Some recent CAD products add-ons such as PTC Pro/Fly-Through, Mechanical Dynamics ADAMS, Matra Datavision's Megavision, Prosolvia Clarus Real-Time Link, and EDS Unigraphics Modelling module follow the same direction, providing real-time visualization capabilities for engineering designs. Systems such as Division's dV/Mock-Up and dV/Reality, only available for PCs and SGI, have started to add to high-performance rendering some limited interaction capabilities and, more importantly, some support for concurrent model design. Working Model 3D, a Windows/NT product by the American company Knowledge Revolution, which concentrates more on motion simulation than on real-time interaction, has been selected by readers of NASA Tech Brief as the most significant new product introduced for the engineering community in 1996. The ongoing ESPRIT project CAVALCADE aims to advance the current state of the art by supporting and enhancing concurrent engineering practices, thanks to a distributed architecture enabling teams based in geographically dispersed locations to collaboratively design, test, validate, and document a shared model.

Simulators and training

One of the most important characteristics of virtual reality is that the user can exploit existing cognitive and motor skills for interacting with the world in a range of sensory modalities and, in many instances, the experience gained in the virtual environment is directly transferable to the real world. This aspects has been put to profit for a variety of simulators and training systems. Many research and industrial applications exist, in diverse domains such as flight simulation [64, 65, 70], driving simulation [10, 54], and surgical simulation [97, 99].

Telepresence and teleoperation

Hostile environments (e.g. damaged nuclear power plants, planets) make it difficult or impossible for human beings to perform maintenance tasks. However, for the foreseeable future, robots will not be intelligent enough to operate with complete independence, but will require operator intervention to perform tasks in changing or unanticipated circumstances.

Telepresence aims to simulate presence of an operator in a remote environment to supervise the functioning of the remote platform and perform tasks controlling remote robots. In supervisory control modes, a virtual reality interface provides the operator with multiple viewpoints of the remote task environment in a multimodal display format that can be easily reconfigured according to changing task priorities. The operator can investigate the remote site either free-flying or through telerobot mounted cameras. To perform remote operations that cannot be performed autonomously by robots, the operator can switch to interactive control. In this telepresence mode, he is given sufficient quantity and quality of sensory feedback to approximate actual presence at the remote site. The operator's stereoscopic display is linked to the robot 3D camera system and his arm is made spatially correspondent with the robot arm. Early works in this area include NASA Ames telepresence prototype application, where the operator interacts with a simulated telerobotic task environment [30]. One of the most advanced applications of this technology is remote surgery [22, 58].

Augmented reality

In augmented reality systems the virtual world is superimposed over the real world, with the intent to supplement it with useful information, for example, guidance in performing a real world task. Only recently the capabilities of real-time video image processing, computer graphic systems and new display technologies have converged to make the display of a virtual graphical image correctly registered with a view of the 3D environment surrounding the user possible.

Researchers working with augmented reality systems have proposed them as a solution in many domains, including military training [90], medical systems [83, 76, 84], engineering and consumer design [2], robotics [24], as well as manufacturing, maintenance and repair [36, 28].

1.2 Origins and Perspectives

In the late 1960's and 1970's, research on a number of fronts formed the basis of virtual reality as it appears today (e.g. head-mounted displays [85, 86], projection-based VR [52, 51]). Virtual environments have existed before that, as telerobotic and teleoperations simulations. The display technology, however, in these cases was usually panel-mounted rather than head-mounted [18] In the mid-1980's, the different technologies that enabled the development of virtual reality converged to create the first true VR systems. At MIT, at the beginning of the 1980's, a limited three-dimensional virtual workspace in which the user interactively manipulates 3D graphical objects spatially corresponding to hand position was developed [79]. In 1984, NASA started the VIVED project (Virtual Visual Environment Display) and later the VIEW project (Virtual Interactive Environment Workstation). As described in Fisher et al. [30], the objective of the research at NASA Ames was to develop a multipurpose, multimodal operator interface to facilitate natural interaction with complex operational tasks and to augment operator awareness of large-scale autonomous integrated systems. The application areas on which NASA Ames focused were telepresence control, supervision and management of large-scaled information systems and human factors research. Even though NASA's research interested researchers, virtual reality was not introduced to the general public until June 6, 1989 at two trade shows by VPL Research and Autodesk, two companies that were involved with NASA projects. Both companies presented devices and head-mounted displays for interacting with virtual worlds. The term "Virtual Reality" was originated at that time by Jaron Lanier, the founder of VPL Research, defining it as "a computer generated, interactive, three-dimensional environment in which a person is immersed." Since then, virtual reality has captured the public imagination and lots of work has been done to explore the possibilities of virtual reality in new areas of application such as medicine, chemistry, scientific visualization.

Although virtual reality technology has been developing over this seemingly long period the possibilities inherent in the new medium have only recently crossed a cultural threshold [13, 12]: that VR has begun to shift away from the purely theoretical and towards the practical. VR system are starting to demonstrate practical effectiveness in real industrial settings (see, for example [93, 5, 40, 29]), showing without questions, that VR technology is starting to hold its promises [98]. Nonetheless, current systems are quite primitive, particularly with respect to their user interfaces [32]. Not only are advances in interface hardware and software required, but a better understanding of many user issues is needed.

2 Requirements

The goal of virtual reality is to put the user in the loop of a real-time simulation, immersed in a world that can be both autonomous and responsive to its actions.

The requirements for virtual reality applications are defined by analyzing the needs in terms of input and output channels for the virtual world simulator.

2.1 User input

The input channels of a virtual reality application are those with which humans emit information and interact with the environment. We interact with the world mainly through locomotion and manipulation, and we communicate information mostly by means of voice, gestures, and facial expressions [8].

Gestural communication as well as locomotion make full body motion analysis desirable, while verbal communication with the computer or other users makes voice input an important option. As stated in the 1995 US National Research Council Report on Virtual Reality [25],

> because human beings constitute an essential component of all [synthetic environment] (SE) systems, there are very few areas of knowledge about human behavior that are not relevant to the design, use, and evaluation of these systems.

However, for practical purposes, it is possible to limit user input to a few selected channels. As the hand offers many more degrees of freedom concentrated in a small area than any other part of the body, hand motion tracking is sufficient for most applications. Moreover, the fact that the hand is our privileged manipulation tool makes hand motion tracking a critical input for interacting with virtual worlds. Viewpoint specification requires real time motion tracking of the user's head, and possibly eyes, in order to update displayed stereo images in coordination with user movements.

2.2 Sensory Feedback

Our sense of physical reality is a construction derived from the symbolic, geometric, and dynamic information directly presented to our senses [18]. The output channels of a virtual reality application correspond thus to our senses: vision, touch and force perception, hearing, smell, taste. Sensory simulation is thus at the heart of virtual reality technology.

2.2.1 Visual Perception

Vision is generally considered the most dominant sense, and there is evidence that human cognition is oriented around vision [50]. High quality visual representation is thus critical for virtual environments. The major aspects of the visual sense that have an impact on display requirements are the following:

- **depth perception**: stereoscopic viewing is a primary human visual mechanism for perceiving depth. However, because human eyes are located only on average 6.3 centimeters apart, the geometric benefits of stereopsis are lost for objects more distant than 30 meters, and it is most effective at much closer distances. Other primary cues (eye convergence and accommodation) and secondary cues (e.g. perspective, motion parallax, size, texture, shading, and shadows) are essential for far objects and of varying importance for near ones;
- **accuracy and field-of-view**: the total horizontal field of vision of both human eyes is about 180 degrees without eye/head movement and 270

with fixed head and moving eyes. The vertical field of vision is typically over 120 degrees. While the total field is not necessary for a user to feel immersed in a visual environment, 90 to 110 degrees are generally considered necessary for the horizontal field of vision [98]; when considering accuracy, the central fovea of a human eye has a resolution of about 0.5 minutes of arc [47];

- **critical fusion frequency**: visual simulations achieve the illusion of animation by rapid successive presentation of a sequence of static images. The critical fusion frequency is the rate above which humans are unable to distinguish between successive visual stimuli. This frequency is proportional to the luminance and the size of the area covered on the retina [23, 55]. Typical values for average scenes are between 5 and 60 Hz [98]. A rule of thumb in the computer graphics industry suggests that below about 10-15 Hz, objects will not appear to be in continuous motion, resulting in distraction [61]. High-speed applications, such as professional flight simulators, require visual feedback frequencies of more than 60 Hz [15].

2.2.2 Sound Perception

Analyzing crudely how we use our senses, we can say that vision is our privileged mean of perception, while hearing is mainly used for verbal communication, to get information from invisible parts of the world or when vision does not provide enough information. Audio feedback must thus be able to synthesize sound, to position sound sources in 3D space and can be linked to a speech generator for verbal communication with the computer. In humans, the auditory apparatus is most efficient between 1000 and 4000 Hz, with a drop in efficiency as the sound frequency becomes higher or lower [98]. The synthesis of a 3D auditory display typically involves the digital generation of stimuli using location-dependent filters. In humans, spatial hearing is performed by evaluating monaural clues, which are the same for both ears, as well as binaural ones, which differ between the two eardrum signals. In general, the distance between a sound source and the two ears is different for sound sources outside the median plane. This is one reason for interaural time, phase and level differences that can be evaluated by the auditory system for directivity perception. These interaural clues are mainly used for azimuth perception (left or right), which is usually quite accurate (up to one degree). Exclusively interaural levels and time differences do not allow univocal spatial perceptions. Monaural cues are mainly used for perceiving elevation. These are amplifications and attenuations in the so-called directional (frequency) bands. Particularly the presence of the external ear (consisting of head, torso, shoulders and pinnae) has decisive impact on the eardrum signals.

2.2.3 Position, Touch and Force Perception

While the visual and auditory systems are only capable of sensing, the haptic sense is capable of both sensing what it is happening around the human being and acting on the environment. This makes it an indispensable part of many human activities and thus, in order to provide the realism needed for effective applications, VR systems need to provide inputs to, and mirror the outputs of, the haptic system. The primary input/output variables for the haptic sense are displacements and forces.

Haptic sensory information is distinguished as either tactile or proprioreceptive information. The difference between these is the following. Suppose the hand grasps an object. The initial feeling (contact) is provided by the touch receptors in the skin, which also provide information on the shape of the object and its texture. If the hand applies more force, proprioreceptive (or kinesthetic) information provides details about the position and motion of the hand and arm, and the forces acting on these, to give a sense of total contact forces, surface compliance, and, very often, weight. In general tactile and kinesthetic sensing occur simultaneously.

To manipulate an object, say move it, rotate it, or pinch it, the haptic system must issue motor action commands that exert forces on the object. These forces are highly dependent on the type of grasping that is used. Power grasping employs all the fingers and the palm, whereas precision grasping uses only the finger-tips.

Two important aspects in force simulation that have an impact on the requirements of a VR systems are the maximum force magnitude and the frequency of force feedback. These depend heavily on application, and research on human factors related to these issues is active [98]. Typical values for simulating interaction with a good variety of objects is at least 10 N at 1 KHz [98].

Another important variable to take in account in VR environments is the human's capability to sense motion and control posture (orientation and balance). The two primary systems playing a role in this perception are the visual and the vestibular systems. We already gave some details about the visual system, it is interesting to remind that the vestibular system also is both a sensor system and a motor system. In its role as a sensory system, the vestibular system provides information about movement of the head and the position of the head with respect to gravity and any other acting inertial forces. As a motor system, the vestibular system plays an important role in posture control, that is, orienting to the vertical, controlling center of mass, and stabilizing the head.

2.2.4 Olfactory Perception

It exists specialized applications where olfactory perception is of importance. One of these is surgical simulation, which need to:

> provide the proper olfactory stimuli at the appropriate moments during the procedure. Similarly, the training of emergency medical personnel operating in the field should bring them into contact with the odors that would make the simulated environment seem more real and which might provide diagnostic information about the injuries that simulated casualty is supposed to have incurred [53]

The main problem about simulating the human olfactory system is, indeed, that a number of questions on how it works remain unanswered. It is certain that the stimuli to the brain cortex are originated in the nose when molecules carrying odors are caught by the receptors neurons, but it is still unknown how the brain generates a recognition pattern isolating some scents from others and reconstructing missing parts. Other sensory systems are strictly tangled with olfaction. It is reported [101] that humans may identify barely one third of the odors while lacking inputs from other senses, like vision. Appropriate color cues improve both accuracy and speed of identification of odors. Human capability of detective odors is quite sensitive, capable of detecting smells in concentration from one part per million to one part per billion, depending on the odor in question. It is much easier to detect increases than decreases in concentration and the magnitude perceived is not linear with changes but closer to a logarithmic relation. A VR environment giving olfactory cues should provide the possibility to diffuse the odors when needed and purify and filter the air when the cue is no longer required.

2.3 Spatiotemporal Realism

The preceding discussion has emphasized the fact that virtual reality applications typically offer multiple input/output modalities and that for each of these modalities timing constraints have to be met in order for applications to be usable (e.g. visual feedback rate $>$ 10 Hz, haptic feedback rate $>$ 1 KHz).

Additional performance constraints derive from the fact that multimodal outputs have to be integrated into a single system. As summarized by Wloka [94], this task is particularly difficult for the following reasons:

> First, the various devices need to display information in tight synchronization, since human tolerances of synchronization errors are quite small. Second, varying delays in the various output

> devices makes proper synchronization even harder. Worse, synchronization errors also result from varying distances between user and devices. (Modern movie soundtracks must take into account the distance sound travels in an average movie theater before reaching the audience.) Third and last, synchronization is not always beneficial. For example, in limited bandwidth, computer-supported cooperative work applications, it is preferable to sacrifice synchronization to enable low-latency, audio-only communication.

Even mono-modal VR applications (e.g. applications with only visual feedback) have to face similar problems, and low-latency constraints have to be met. In this case, synchronization is between synthesized and real-world sensory input.

Human beings are very sensitive to these problems. For instance, it has been reported that, depending on the task and surrounding environment, lag of as little as 100 ms degrades human performance [57, 42] and, if lag exceeds 300 ms, humans start to dissociate their movements from the displayed effects, thus destroying any immersive effects [42].

Immersion in virtual reality environments has been shown to result in problems of disorientation and nausea similar to the symptoms of motion sickness, and it has been demonstrated that lag and synchronization problems are a major influencing factor [19, 72, 49, 95]. Simulator and motion sickness are generally considered to be caused by conflicts between the information received from two or more sensory systems [71]. Sensory conflict alone is not sufficient to explain the development of simulator sickness, since it takes no account of the adaptive capabilities of the human body. To take account of habituation, the concept of sensory conflict has been extended into a theory of sensory rearrangement, which states that:

> all situations which provoke motion sickness are characterized by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular system and the non-vestibular proprioreceptors are at variance either with one another or with what is expected from previous experience. [71]

This means that spatio-temporal realism, i.e. the ability to meet synchronization, lag, and accuracy constraints within low tolerances, is a required feature for all virtual reality system. Quantifying exactly absolute and task-depending tolerance limits is an open research subject. The development of a comprehensive review of theory and data on human performance characteristics from the viewpoint of synthetic environment systems is one recommended research priority identified by the Committee on Virtual Reality Research and Development of the U.S. National Research Council [25].

2.4 Discussion

The analysis of the requirements in terms of input and output channels has highlighted fidelity and performance requirements for the bare simulation of existence of synthetic objects.

Successful virtual reality applications must combine new input and output devices in ways that provide not only such an illusion of existence of synthetic objects, but also the interaction metaphors for interacting with them. An ACM CHI workshop on the challenges of 3D interaction [43] has identified five types of characteristics that 3D user interfaces must have to exploit the perceptual and spatial skills of users. These are summarized as follows:

- **Multiple/integrated input and output modalities.** User interfaces should be able to use more than just the visual channel for communications.
- **Functional fidelity**. Taken together, the various sensory cues provided by an interface must be appropriate to the task being performed.
- **Responsiveness**. 3D user interfaces must be very quick to respond to user actions so that natural and explorative behavior can occur. This introduces important timing constraints on the applications.
- **Affordances**. Affordances allow the creation of objects that have meaningful properties and provide clues about how to interact with 3D objects and environments.
- **Appeal to mental representation**. User interfaces must be organized in a way that they are recognizable by users. Real-world metaphors and physical simulation techniques are especially helpful with this respect.

These characteristics pose important challenges both to the hardware side of virtual reality systems, in terms of devices that have to be used to communicate to and with users, and to the software side, in terms of techniques that have to be developed to efficiently support multimodal interaction in a time-critical setting. These aspects are reviewed in the following chapters of this report.

3 Enabling Technology: Hardware

Currently, a set of devices, hand measurement hardware, head-mounted displays, as well as 3D audio systems, speech synthesis or recognition systems are available on the market. At the same time, many research labs are working on defining and developing new devices such as tactile gloves and eye-tracking devices, or on improving existing devices such as force feedback devices, head-mounted displays and tracking systems. In the next sections, we are going to present various existing devices and a perspective of development for the future. There exists a number of surveys collecting information on the subject (e.g. [98, 56, 1]) treating more extensively the matter.

3.1 User input

3.1.1 Position/Orientation Tracking

Head tracking is the most valuable input for promoting the sense of immersion in a VR system. The types of trackers developed for the head also can be mounted on glove or body suit devices to provide tracking of a user's hand or some other body part. Many different technologies can be used for tracking. Mechanical systems measure change in position by physically connecting the remote object to a point of reference with jointed linkages; they are quite accurate, have low lag and are good for tracking small volumes but are intrusive, due to tethering and subject to mechanical part wear-out. Magnetic systems couple a transmitter producing magnetic fields and a receiver capable to determine the strength and angles of the fields; they are quite inexpensive and accurate and accommodate for larger ranges, the size of a small room, but they are subject to field distortion and electromagnetic interference. Optical systems can use a variety of detectors, from ordinary video cameras to LED's, to detect either ambient light or light emitted under control of the position tracker (infrared light is often used to prevent interference with other activities); they can work over a large area, are fast and are not subject to interferences but are heavy and expensive. Acoustic (ultrasound) systems use three microphones and three emitters to compute the distance between a source and receiver via triangulation; they are quite inexpensive and lightweight but subject to noise interference and yield low accuracy since speed of sound in air varies and there can be echoes. Inertial systems use accelerometers and gyroscopes to compute angular velocity about each axis and changes in position; they are unlimited in range and fast but can detect only 3 DOF and are not accurate for slow position changes. The price range of these systems is quite large: from less than 1,000 ECU for the cheapest acoustic and magnetic systems to more than 60,000 ECU of the most sophisticated ones. The resolution offered is, typically, around 0.1 mm for translations and 0.1^{o} for rotations

3.1.2 Eye Tracking

Eye trackers work somewhat differently: they do not measure head position or orientation but the direction at which the users' eyes are pointed out of the head. This information is used to determine the direction of the user's gaze and to update the visual display accordingly. The approach can be optical, electroocular, or electromagnetic. The first of these, optical, uses reflections from the eye's surface to determine eye gaze. Most commercially available eye trackers are optical, they usually illuminate the eye with IR LED's, generating corneal reflections. Electroocular approaches use an electrooculogram (EOG) via skin electrodes that provide measurement of the corneoretinal potential generated within the eyeball by the metabolically active retinal epithelium. There is availability of, at least, one commercial product based on this approach. It has the advantage to be totally non-invasive, but it is less stable and needs more often to be recalibrated. Electromagnetic approaches determine eye gaze based on measurement of magnetically induced voltage on a coil attached to a lens on the eye. All the commercial products are quite expensive, ranging from approximately 15,000 ECU up to almost 100,000 and offer good frequency response (up to 500 Hz).

3.1.3 Full Body Motion

There are two kinds of full-body motion to account for: passive motion, and active self-motion. The first is quite feasible to simulate vehicles with current technology. The usual practice is to build a "cabin" that represents the physical vehicle and its controls, mount it on a motion platform, and generate virtual window displays and motion commands in response to the user's operation of the controls. They are usually specialized for particular application (e.g., flight simulators) and they represented the first practical VR applications for military and pilots' training use. More recently this technology have been extensively used by the entertainment industry. Self-motion interfaces, instead, are defined as those cases where the user moves himself through a VR environment. This is typically performed linking the body to a gyroscope, giving a 360^{o} range of motion in pitch, roll and yaw. All these systems are usually quite expensive, from 6,000 ECU to 50,000 ECU.

3.2 Sensory Feedback

3.2.1 Visual Feedback

Humans are strongly oriented to their visual sense: they give precedence to the visual system if there are conflicting inputs from different sensory modalities. Visual displays used in a VR context should guarantee stereoscopic vision and the ability to track head movements and continually update the visual display to reflect the user's movement through the environment. In addition, the user should receive visual stimuli of adequate resolution, in full color, with adequate brightness, and high-quality motion representations.

Many different techniques provide stereoscopic vision: head mounted displays (HMDs), shutter glasses, passive glasses, and booms. Currently

HMDs use separate displays mounted in a helmet for each eye. New versions of HMDs, still under development, are based on the creation of the image directly on the retina, using a beam of light. With shutter glasses the user wear a pair of glasses where each lens is substituted with an electronic shutter (a monochrome LCD). Looking at a CRT showing left and right images synchronized with them, the shutters are alternatively opaque or transparent. Passive glasses use an approach in which perspective views for each eye are encoded in the form of either color or polarization of the light, with the "lens" for each eye containing a filter that passes only the appropriate image intended for each eye. A boom is a system using two monitors (CRT or LCD) and special optics to present a different image to each eye, mounted in a device suspended from a boom in front of the user.

The vast majority of current commercial products are HMDs ranging from high-end, expensive products priced around 50,000 ECU to quite inexpensive consumer product displays costing less than 1,000 ECU. Shutter glasses are generally inexpensive and booms are definitely the more expensive, reaching prices over 80,000 ECU. The resolution range from 320×400 of the cheapest devices to the 1280×1024 with a horizontal field of view up to 140^o.

3.2.2 Haptic Feedback

At the current time, tactile feedback is not supported in practical use, that is, tactile systems are not in everyday use by users (as opposed to developers). Tactile stimulation can be achieved in a number of different ways. Those presently used in VR systems include mechanical pins activated by solenoid, piezoelectric crystal where changing electric fields causes expansion and contraction, shape-memory alloy technologies, voice coils vibrating to transmit low amplitude, high frequency vibrations to the skin, several kinds of pneumatic systems (air-jets, air-rings, bladders), and heat pump systems. Other technologies, such as electrorheological fluids that harden under the application of an electric field are currently being investigated. Only one commercial system is known to provide temperature feedback, not coupled to tactile. The maximum resolution obtainable is around 1 mm and the price range is between 1,000 ECU and 10,000 ECU.

Kinesthetic interfaces, instead, are much more developed and in common use. Essentially, there are three components to providing a force feedback interface for VR systems: measurement of the movement of the user's fingers, hand, and/or arm, and sensing any forces he exerts; calculation of the effect of the exerted forces on objects and the resultant forces that should act on the user; and presentation of these resultant forces to the user's fingers, wrist, and arm as appropriate. The technologies in current use to provide force feedback are: electromagnetic motors that produce torque with two time-varying magnetic fields, hydraulics systems where a hydraulic fluid is pressurized and, under the control of valves, delivered to actuators and pneumatics systems using pressurized gases. Piezoelectric and magnetorestrictive technologies are still the subject of research and development. The available systems can offer from 3 up to 8 DOF, simulate forces up to 10 N (peak) and, for the ones for which price is available, cost from 6,000 ECU to 20,000 ECU.

3.2.3 Sound Feedback

The commercial products available for the development of 3-D sounds (sounds apparently originating from any point in a 3-D environment) are very different in quality and price. They range from low-cost, PC-based, plug-in technologies that provide limited 3-D capabilities to professional quality, service-only technologies that provide true surround audio capabilities. Applications for them range from video games to military simulations, from consumer electronic to professional post-processing.

Some of these systems can generate multiple sounds at a time, possibly 2-D and 3-D together. Other interesting features are: Doppler shifts simulation with the sounds changing while travelling past the listener, control of reverb reflections, possibility to perform an acoustic ray-tracing of rooms and environments. Depending upon the chosen systems, the sounds are delivered to the user by speakers or earphones. The prices range from 1,000 ECU to 10,000 ECU and the quality of the sampling is typically the CD one (44.1 KHz).

3.2.4 Olfactory Feedback

Devices used to collect and interpret odors are usually referred to as artificial or electronic noses and use three basic technologies: gas chromatography, mass spectrometry and chemical array sensors.

Among the various technologies used to deliver odors, perhaps the most mature is odorant storage. Odorants can be stored under several different forms: liquid, gels or waxes. Most usually they are microencapsulated on flat surfaces. The system releases the odors scratching the desired amount of capsules, so discretely metering the dosage. Capsules can contain droplets of liquid ranging from 10 to 1000 μm in a neutral layer of gelatin.

Current market available systems use air streams to actually deliver the smell to the user. The odorants are dissolved in a solvent gas, such as carbon dioxide, and then directed to the user's nose through a hose. Several available technologies are considered to be used for odor delivery inside a HMD. Such portable system has to be miniaturized and lightweight and have low power requirements. Ink-jet printer nozzles are good candidates since they allow precise control of some odorants. The number of odors currently available in a single system ranges from 6-7 to almost 20 and there are researches trying to simulate special odors needed for particular application like human odors (e.g., blood, liver) in surgical simulation.

3.3 Conclusions

At the present time a good choice of commercial products exists for visual, tracking, and user input interfaces. Auditory and haptic interface technologies currently are almost restricted to research applications, but are becoming ready for use in practical applications. Full-body motion interfaces are limited to specialized entertainment systems, support for more general types of movement still is exclusively a research topic. Olfactory interface is the least mature of all the technologies.

Even the most mature technologies (visual and tracking) still suffer from some limitations, and in no instance VR interface technology perfectly match human sensory capabilities. It is important to note, however, that it now possible, as opposed to the situation of only a few years ago, to have devices that provide a fairly good quality and are useable for many, if not all, applications.

As full fidelity of sensory cues is not achievable even with the most advanced and expensive devices, it is thus of primary importance when developing a VR application, to carefully study the specific fidelity required and the most appropriate devices and trade-offs needed for satisfying those requirements at best.

4 Enabling Technology: Software

The difficulties associated with achieving the key goal of immersion has led the research in virtual environments to concentrate far more on the development of new input and display devices than on higher-level techniques for 3D interaction. It is only recently that interaction with synthetic worlds has tried to go beyond straightforward interpretation of physical device data [44].

4.1 Problems to face

User interfaces software is intrinsically difficult to design and implemented, and there are reasons why this type of software will always be among the most complex to create. Developing virtual reality applications is an even harder challenge, since it involves the creation of a software system with strict quality and timing constraints dictated by the needs of sensory simulation and direct 3D interaction.

A number of authors have analyzed these problems [87, 38, 77, 66, 80, 31, 92, 37, 88, 60, 41]. Their findings are summarized here.

4.1.1 Man-machine communication

Interactive programs have to establish a bidirectional communication with humans. Not only they have to let humans modify information, but they have to present it in a way to make it simple to understand, to indicate what types of manipulations are permitted, and to make it obvious how to do it. As noted by Marcus [60], awareness of semiotic principles, in particular the use of metaphors, is essential for researchers and developers in achieving more efficient, effective ways to communicate to more diverse user communities. As a common vocabulary is the first step towards effective communication, user-interface software development systems should assist developers by providing implementations of standard interaction metaphors. This has been a very successful approach for 2D interfaces. Recent research in the 3D interaction field has focused on exploring responsive 3D interfaces with better affordances, functional fidelity and mental appeal [21, 11]. Growing the vocabulary of 3D interaction metaphors is an active research subject.

4.1.2 Iterative construction

Good user interfaces are "user friendly" and "easy to use". These are subjective qualities, and, for this reason, as stated by Myers,

> the only reliable way to generate quality interfaces is to test prototypes with users and modify the design based on their comments. [66]

Multiple iteration of the classic design-implement-test cycle have to be done, and it is difficult to evaluate the time that has to be spent before validation. A classic survey on user interface programming [67] reports that more than 90% of the projects analyzed that included a user interface used an iterative approach to design and implementation. The same report shows that in today's applications, an average of 48% of the code is devoted to the user interface portion. The report underlines the importance of user interface tools, such as toolkits, user interface management systems, or graphical user interface builders.

In the case of virtual environment, no standard solution exists [41]. The design of software architectures to support construction and rapid prototyping of three dimensional interfaces, interactive illustrations, and three dimensional widgets is an important area of research.

4.1.3 Parallel programming

Interactive applications have to model user interaction with a dynamically changing world. In order for this to be possible, it is necessary for applications to handle within a short time real-world events that are generated in an order that is not known before the simulation is run. Thus, user interface software is inherently parallel, and some form of parallelism, from quasi-parallelism, to pseudo-parallelism to real parallelism has to be used for its development.

All problems inherent to parallel programming have thus to be solved (e.g., synchronization, maintenance of consistency, protection of shared data) [66].

Furthermore, the multimodal aspect of virtual environment applications impose the use of true parallelism [82], as the various components of an applications have to receive input and produce output at considerably variable rates (e.g., 10 Hz for visual feedback and 1 KHz for haptic feedback).

4.1.4 Performance

Virtual reality applications have very stringent performance requirements. In particular, low visual feedback bandwidth can destroy the illusion of animation, while high latency can induce simulation sickness and loss of feeling of control. In order to be spatio-temporally realistic, and thus effectively useable, applications should meet latency and visual feedback constraints. This high sensitivity of humans to latency and visual feedback rates frequency requires that appropriate techniques be used in VR applications to minimize the latency and maximize the feedback frequency. These two aspects are related but are not the same thing: for instance, using pipelined multiprocessing to increase computation speed is a way to probably increase feedback frequency that is likely to also increase application latency [95]. For this reason, simply optimizing standard applications is not sufficient.

4.1.5 Robustness

The contract model of software programming [63] is a way to specify and understand the behavior of software units. With this model, precondition and postcondition describe the benefits and obligation in the software contract that relates the software unit supplier to its clients. User interface software units is forced to have weak preconditions, since few assumptions can be made on the behavior of the external world. This makes its realization and verification more difficult.

4.1.6 Modularization

The ease of creation and maintenance of a piece of software is improved by decoupling it in units with very weak coupling, so as to develop and test them in isolation. Unfortunately, a complete separation between user interface and application is very difficult to obtain. In particular, the need of semantic feedback associated to the different operation tends to increase the coupling among application and interface components. This fact often forces a change in application parts because of changes in the user interface [77].

4.1.7 Information presentation

Presenting information in 3D space introduces problems which are not present in classical 2D interfaces. In particular, occlusion and perspective effects offer both new possibilities and new challenges to visualization. Treating 3D information is more complex than treating the 2D counterpart (e.g., because of the complexity of 3D geometric space) and, in particular, 3D manipulation requires more dexterity. A notable example demonstrating the potential of 3D interfaces for information presentation is Xerox Parc's Information Visualizer. Built using the Cognitive Coprocessor architecture, it takes advantage of the greater possibilities of 3D with novel means of information presentation, such as the cone tree and the perspective wall [17, 74, 59, 73].

4.1.8 Perceptual requirements

The perceptual requirements of virtual reality application, summarized earlier in this report, are more complex to satisfy that those of standard graphical applications.

4.2 Software solutions

The fact that virtual reality software is intrinsically difficult to design and implement emphasizes the importance of user interface tools, such as toolkits, frameworks, user interface management systems, or graphical user interface builders.

Current systems to support virtual reality software construction are subdivided into two categories: toolkits and authoring systems. Toolkits are programming libraries that provide a set of functions for supporting the creation of a virtual reality application. Authoring systems are complete programs with graphical interfaces for creating worlds without resorting to detailed programming. These usually include some sort of scripting language in which to describe complex actions (e.g., VRML, which is becoming a defacto standard for describing virtual worlds). While simpler to use, current authoring system do not offer all the functionalities of toolkits.

At the current state of the art, no single system supports satisfactorily all the aspects of creation of a virtual reality application [94]. Most of the time, different systems have to be combined, and ad-hoc solutions implemented to integrate them in a working application. A typical VR toolkit provides supports for high-speed rendering (mostly through the use of some form of level-of-detail modeling), low-level interfacing with a variety of input devices (at the minimum supporting high frequency sensor reading for input and a variety of graphics display formats for output), a few built-in interaction metaphors (at the minimum for viewpoint/object motion and picking), graphical database support with converters to/from a variety of formats, and an event model for interactive application programming. Tools of this kind range from zero or low-cost solution (e.g., Rend386, Superscape, OpenGL Optimizer) to high-end "professional" packages (e.g., Division dVS and dVise, Sense8 World Tool Kit WTK). The increased power of parallel processing is essential to meet timing constraints in real applications [95], and for this reason high-end graphics systems are network-parallel or MP-parallel [4, 33, 20, 75, 81]. No system to date, however, incorporates appropriate support to time-critical graphics and low-latency synchronization schemes [96, 91].

In addition to generic support systems, a variety of software tools exist to solve specific problems. Examples are domain-specific toolkits for supporting distributed application [27, 89], libraries for implementing high-speed collision detection [45], and tools for supporting physical simulation with haptic feedback [78, 16]. In parallel, a few toolkits, such as UGA [100], VB2 [33], Alice [69], and OpenInventor [68], provide support for 3D interaction techniques that go beyond the standard picking and viewpoint/object motion, implementing in particular 3D widgets or virtual tools.

Considerable advances have been made in the last few years in the domain of algorithms and software libraries for virtual reality. In the words of Linda Jacobson:

> We now posses the algorithms, architecture and hardware. We know the techniques. [46]

One of the main priorities for research, now, is the creation of appropriate dynamic graphics architectures for their integration in a time critical setting [92].

5 Concluding Remarks

Virtual environment technology has been developing over a long period, and offering presence simulation to users as an interface metaphor to a synthesized world has become the research agenda for a growing community of researchers and industries. Considerable achievements have been obtained in the last few years, and we can finally say that virtual reality is here, and is here to stay. More and more research has demonstrated its usefulness both from the evolutionary perspective of providing a better user interface and from the revolutionary perspective of enabling previously impossible applications. Examples of applications areas that have benefited from VR technology are virtual prototyping, simulation and training, telepresence and teleoperation, and augmented reality. Virtual reality has thus finally begun to shift away from the purely theoretical and towards the practical.

Nonetheless, writing professional virtual reality applications remains an inevitably complex task, since it involves the creation of a software system with strict quality and timing constraints dictated by human factors. Given the goals of virtual reality, this complexity will probably be always there [91].

The marketing situation of VR is very fluid. This means that the technology while being ready for professional applications is not at the stage of settling definite standards and definite reference points in all perspectives, including possible leading manufacturers, compatibility specifications, performance levels, economical costs and human expertise. This uncertainty should not be confused with lack of confidence on the promising outcomes of the technology, but instead with the rapid mutation and evolution that characterizes the field, perhaps even more than for other information technology markets.

From the hardware point of view, while full fidelity of sensory cues is still not achievable even with the most advanced and expensive devices, there exists now a variety of research and commercial solutions successfully useable for practical applications.

For a large number of application domains, the major limitation is now provided by software since, at the current state of the art, no single system supports satisfactorily all the aspects of creation of a virtual reality application [94]. Most of the time, different packages have to be combined, and ad-hoc solutions implemented to integrate them in a working application. In particular, the creation of appropriate time-critical multimodal VR architectures is an open research topic [92, 95].

In addition to further research and development on actual hardware and software issues, all the areas of VR technology would benefit from research aimed at better understanding the role of sensory cues and human perceptual issues. This improved understanding not only is required to know how sensory cues can be delivered or simulated, but when and how they should be used [98].

As a conclusion, we can say that given the complexity of VR, the importance of human factors, and the lack of standard solutions, the secret of successfully implementing professional VR applications is to set realistic expectations for the technology [56]. It is common to have misconceptions on what VR can and cannot do, and to have negative reactions when noticing that VR "is not that real". As for all technologies, but more importantly for a much emphasized and complex technology such as VR, it is important to choose appropriate applications with well define functionality objectives, to compare the abilities of VR with competing technologies for reaching those objectives, to ensure that the VR solution can be integrated with standard business practices, and to choose the right set of tools and techniques [56].

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