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Virtual Reality

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Abstract:
Virtual Reality (VR), sometimes called Virtual Environments (VE) has drawn much attention in the last few years. Extensive media coverage causes this interest to grow rapidly. Very few people, however, really know what VR is, what its basic principles and its open problems are. In this paper a historical overview of virtual reality is presented, basic terminology and classes of VR systems are listed, followed by applications of this technology in science, work, and entertainment areas. An insightful study of typical VR systems is done. All components of VR application and interrelations between them are thoroughly examined: input devices, output devices and software. Additionally human factors and their implication on the design issues of VE are discussed. Finally, the future of VR is considered in two aspects: technological and social. New research directions, technological frontiers and potential applications are pointed out. The possible positive and negative influence of VR on life of average people is speculated.

1. Introduction:
1.1. History:
Nowadays computer graphics is used in many domains of our life. At the end of the 20^{th} century it is difficult to imagine an architect, engineer, or interior designer working without a graphics workstation. In the last years the stormy development of microprocessor technology brings faster and faster computers to the market. These machines are equipped with better and faster graphics boards and their prices fall down rapidly.

It becomes possible even for an average user, to move into the world of computer graphics. This fascination with a new (ir)reality often starts with computer games and lasts forever. It allows to see the surrounding world in other dimension and to experience things that are not accessible in real life or even not yet created. Moreover, the world of three-dimensional graphics has neither borders nor constraints and can be created and manipulated by ourselves as we wish – we can enhance it by a fourth dimension: the dimension of our imagination.

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But not enough: people always want more. They want to step into this world and interact with it – instead of just watching a picture on the monitor. This technology which becomes overwhelmingly popular and fashionable in current decade is called Virtual Reality (VR). The very first idea of it was presented by Ivan Sutherland in 1965: “make that (virtual) world in the window look real, sound real, feel real, and respond realistically to the viewer’s actions” [Suth65]. It has been a long time since then, a lot of research has been done and status quo: “the Sutherland’s challenge of the Promised Land has not been reached yet but we are at least in sight of it” [Broo95]. Let us have a short glimpse at the last three decades of research in virtual reality and its highlights [Bala93a, Cruz93a, Giga93a, Holl95]:

• The Ultimate Display:

In 1965 Ivan Sutherland proposed the ultimate solution of virtual reality: an artificial world construction concept that included interactive graphics, force-feedback, sound, smell and taste.

• "The Sword of Damocles":

The first virtual reality system realized in hardware, not in concept. Ivan Sutherland constructs a device considered as the first Head Mounted Display (HMD), with appropriate head tracking. It supported a stereo view that was updated correctly according to the user's head position and orientation.

• GROPE:

The first prototype of a force-feedback system realized at the University of North Carolina (UNC) in 1971.

• VIDEOPLACE:

Artificial Reality created in 1975 by Myron Krueger – "a conceptual environment, with no existence". In this system the silhouettes of the users grabbed by the cameras were projected on a large screen. The participants were able to interact one with the other thanks to the image processing techniques that determined their positions in 2D screen's space.

• VCASS:

Thomas Furness at the US Air Force's Armstrong Medical Research Laboratories developed in 1982 the Visually Coupled Airborne Systems Simulator – an advanced flight simulator. The fighter pilot wore a HMD that augmented the out-the window view by the graphics describing targeting or optimal flight path information.

• VIVED :

VIrtual Visual Environment Display – constructed at the NASA Ames in 1984 with off-the-shelf technology a stereoscopic monochrome HMD.

• VPL:

The VPL company manufactures the popular Data Glove (1985) and the Eye Phone HMD (1988) – the first commercially available VR devices.

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• BOOM:

Commercialized in 1989 by the Fake Space Labs. BOOM is a small box containing two CRT monitors that can be viewed through the eye holes. The user can grab the box, keep it by the eyes and move through the virtual world, as the mechanical arm measures the position and orientation of the box.

• UNC Walkthrough Project:

In the second half of 1980s at the University of North Carolina an architectural walkthrough application was developed. Several VR devices were constructed to improve the quality of this system like: HMDs, optical trackers and
the Pixel-Plane graphics engine.

• Virtual Wind Tunnel:

Developed in early 1990s at the NASA Ames application that allowed the observation and investigation of flow-fields with the help of BOOM and Data Glove (see also section 1.3.2).

• CAVE:

Presented in 1992 CAVE (CAVE Automatic Virtual Environment) is a virtual reality and scientific visualization system. Instead of using a HMD it projects stereoscopic images on the walls of room (user must wear LCD shutter glasses). This approach assures superior quality and resolution of viewed images, and wider field of view in comparison to HMD based systems (see also section 2.5.1).

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• Augmented Reality (AR):
A technology that "presents a virtual world that enriches, rather than replaces the real world" [Brys92c]. This is achieved by means of see-through HMD that superimposes virtual three-dimensional objects on real ones. This technology was previously used to enrich fighter pilot's view with additional flight information (VCASS). Thanks to its great potential – the enhancement of human vision – augmented reality became a focus of many research projects in early 1990s (see also section 1.3.2).

1.2. What is VR? What is VR not?

At the beginning of 1990s the development in the field of virtual reality became much more stormy and the term Virtual Reality itself became extremely popular. We can hear about Virtual Reality nearly in all sort of media, people use this term very often and they misuse it in many cases too. The reason is that this new, promising and fascinating technology captures greater interest of people than e.g., computer graphics. The consequence of this state is that nowadays the border between 3D computer graphics and Virtual Reality becomes fuzzy. Therefore in the following sections some definitions of Virtual Reality and its basic principles are presented.

1.2.1. Some Basic Definitions and Terminology

Virtual Reality (VR) and Virtual Environments (VE) are used in computer community interchangeably. These terms are the most popular and most often used, but there are many other. Just to mention a few most important ones: Synthetic Experience, Virtual Worlds, Artificial Worlds or Artificial Reality. All these names mean the same:

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• "Real-time interactive graphics with three-dimensional models, combined with a display technology that gives the user the immersion in the model world and direct manipulation." [Fuch92]

• "The illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on a three-dimensional, stereoscopic head-tracker displays, hand/body tracking and binaural sound. VR is an immersive, multi-sensory experience." [Giga93a]

• "Computer simulations that use 3D graphics and devices such as the DataGlove to allow the user to interact with the simulation." [Jarg95]

• "Virtual reality refers to immersive, interactive, multi-sensory, viewer-centered, three dimensional computer generated environments and the combination of technologies required to build these environments." [Cruz93a]

• "Virtual reality lets you navigate and view a world of three dimensions in real time, with Six degrees of freedom. (...) In essence, virtual reality is clone of physical reality." [Schw95]

Although there are some differences between these definitions, they are essentially equivalent. They all mean that VR is an interactive and immersive (with the feeling of presence) experience in a simulated (autonomous) world [Zelt92] (see fig. 1.2.1.1) – and this measure we will use to determine the level of advance of VR systems.

(0,0,0) (1,1,1)

Presence
Interaction
Autonomy

Virtual Reality
(0, 0,1) (0, 1,1)
(1, 0,1)
(1, 0,0) (1, 1,0)
(0, 1,0)

Figure 1.2.1.1. Autonomy, interaction, presence in VR – Zeltzer's cube (adapted from [Zelt92]).

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Many people, mainly the researchers use the term Virtual Environments instead of Virtual Reality "because of the hype and the associated unrealistic expectations" [Giga93a]. Moreover, there are two important terms that must be mentioned when talking about VR: Telepresence and Cyberspace. They are both tightly coupled with VR, but have a slightly different context:

• Telepresence :
Is a specific kind of virtual reality that simulates a real but remote (in terms of distance or scale) environment. Another more precise definition says that telepresence occurs when "at the work site, the manipulators have the dexterity to allow the operator to perform normal human functions; at the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite" [Held92].

• Cyberspace:
was invented and defined by William Gibson as "a consensual hallucination experienced daily by billions of legitimate operators (...) a graphics representation of data abstracted from the banks of every computer in human system" [Gibs83]. Today the term Cyberspace is rather associated with entertainment systems and World Wide Web (Internet).

1.2.2. Levels of Immersion in VR Systems:

In a virtual environment system a computer generates sensory impressions that are delivered to the human senses. The type and the quality of these impressions determine the level of Immersion and the feeling of presence in VR. Ideally the high-resolution, high-quality and Consistent over all the displays, information should be presented to all of the user's senses [Slat94]. Moreover, the environment itself should react realistically to the user's actions.

The practice, however, is very different from this ideal case. Many applications stimulate only one or a few of the senses, very often with low-quality and unsynchronized information. We can group the VR systems accordingly to the level of immersion they offer to the user (compare with [Isda93, Schw95]):

• Desktop VR:
Sometimes called Window on World (Wow) systems. This is the Simplest type of virtual reality applications. It uses a conventional monitor to display the Image (generally monoscopic) of the world. No other sensory output is supported.

• Fish Tank VR:
Improved version of Desktop VR. These systems support head tracking and therefore improve the feeling of "of being there" thanks to the motion parallax effect. They still use a conventional monitor (very often with LCD shutter glasses for stereoscopic viewing) but generally do not support sensory output.

• Immersive Systems:
The ultimate version of VR systems. They let the user totally immerse in computer generated world with the help of HMD that supports a stereoscopic View of the scene accordingly to the user's position and orientation. These systems may be enhanced by audio, haptic and sensory interfaces

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1.3. Applications of VR

1.3.1. Motivation to use VR

Undoubtedly VR has attracted a lot of interest of people in last few years. Being a new paradigm of user interface it offers great benefits in many application areas. It provides an easy, powerful, intuitive way of human-computer interaction. The user can watch and manipulate the simulated environment in the same way we act in the real world, without any need to learn how the complicated (and often clumsy) user interface

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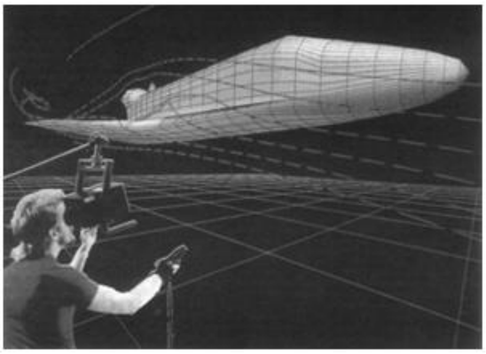
works. Therefore many applications like flight simulators, architectural walkthrough or data visualization systems were developed relatively fast. Later on, VR has was applied as a teleporting and collaborative medium, and of course in the entertainment area. just to mention the visualization of St. Peter Basilica at the Vatican presented at the Virtual Reality World'95 congress in Stuttgart or commercial Virtual Kitchen design tool. What is so Fantastic about VR to make it superior to a standard computer graphics? The feeling of presence And the sense of space in a virtual building, which cannot be reached even by the most realistic Still pictures or animations. One can watch it and perceive it under different lighting conditions just like real facilities. One can even walk through non-existent houses – the destroyed ones (See fig. 1.3.2.1) like e.g., the Frauenkirche in Dresden, or ones not even created yet.

Another discipline where VR is also very useful is scientific visualization. The navigation Through the huge amount of data visualized in three-dimensional space is almost as easy as Walking. An impressive example of such an application is the Virtual Wind Tunnel [Brys93f, Brys93g] developed at the NASA Ames Research Center. Using this program the scientists Have the possibility to use a data glove to input and manipulate the streams of virtual smoke in the airflow around a digital model of an airplane or space-shuttle. Moving around (using a BOOM display technology) they can watch and analyze the dynamic behavior of airflow and

easily find the areas of instability (see fig. 1.3.2.2). The advantages of such a visualization system are convincing – it is clear that using this technology, the design process of complicated shapes of e.g., an aircraft, does not require the building of expensive wooden models any more. It makes the design phase much shorter and cheaper.

The success of NASA Ames Encouraged the other companies to build similar installations – at Eurographics'95 Volkswagen in cooperation with the German Fraunhofer Institute presented a prototype of a virtual wind



Exploration of airflow using Virtual Wind Tunnel developed at NASA Ames: (a) Outside view, (b) inside view (from [Brys93f]). Other disciplines of scientific visualization that have also profited of virtual reality include visualization of chemical molecules

Modeling, Designing and Planning:

In modeling virtual reality offers the possibility of watching in real-time and in real-space what The modeled object will look like. Just a few prominent examples: developed at the Fraunhofer Institute Virtual Designor mentioned already before Virtual Kitchen – toolsfor interior designers who can visualize their sketches. They can change colors, textures and positions of objects, observing instantaneously how the whole surrounding would look like. VR was also successfully applied to the modeling of surfaces [Brys92b, Butt92, Kame93]. The advantage of this technology is that the user can see and even feel the shaped surface under his/her fingertips.

Although these works are pure laboratory experiments, it is to believe that great applications are possible in industry e.g., by constructing or improving car or aircraft body shapes directly in the virtual wind tunnel!

Training and Education:

The use of flight simulators has a long history and we can consider them as the precursors of today's VR. First such applications were reported in late 1950s [Holl95], and were constantly improved in many research institutes mainly for the military purposes [Vinc93]. Nowadays they are used by many civil companies as well, because they offer lower operating costs than the real aircraft flight training and they are much safer In other disciplines where training is necessary, simulations have also offered big benefits. Therefore they were prosperously applied for determining the efficiency of virtual reality training of astronauts by performing hazardous tasks in the space [Cate95]. Another applications that allow training of medicine students in performing end surgery [McGo94], operations of the eye [Hunt93, Sinc94] and of the leg [Piep93] were proposed in recent years and finally a virtual baseball coach [Ande93] has a big potential to be used in training and in entertainment as well. One can say that virtual reality established itself in many disciplines of human activities, as a medium that allows easier perception of data or natural phenomena appearance. Therefore the Education purposes seem to be the most natural ones. The intuitive presentation of construction rules (virtual Lego-set), visiting a virtual museum, virtual painting studio or virtual music playing [Loef95, Schr95] are just a few examples of possible applications. And finally thanks to the enhanced user interface with broader input and output channels, VR allows people with disabilities to use computers [Trev94, Schr95].

Telepresence and Teleoperating:

Although the goal of telerobotics is autonomous operation, a supervising human operator is still required in most of cases [Bola93]. Telepresence is a technology that allows people to operate in remote environments by means of VR user interfaces In many cases this form of remote control is the only possibility: the distant environment may behazardous to human health or life, and no other technology supports such a high level ofdexterity of operation. presents an example of master and slave parts of ateleoperating system. The nanomanipulator project [Tayl93] shows a different aspect of telepresence – operating in environment, remote in terms of scale. This system that uses a HMD and force-feedback manipulation allows a scientist to see a microscope view, feel and manipulate the surface of the sample. As the same category, the mentioned already before eye surgery system [Hunt93], might be considered: beyond its training capabilities and remote operation, it offers the scaling of movements (by factor 1 to 100) for precise surgery. In fact it may be also called a centimanipulator.

Cooperative Working:

Network based, shared virtual environments are likely to ease the collaboration between remote users. The higher bandwidth of information passing may be used for cooperative working. The big potential of applications in this field, has been noticed and multi-user VR becomes the focus of many research programs like NPSNET [Mace94, Mace95b], AVIARY [Snow94a] and others [Fahl93, Giga93b, Goss94]. Although these projects are very promising, their realistic value will be determined in practice. Some practical applications, however, already do exist – just to mention a collaborative CO-CAD desktop system [Gisi94] that enables a group of engineers to work together within a shared virtual workspace. Other significant examples of distributed VR systems are training applications: in inspection of hazardous area by multiple soldiers [Stan94] or in performing complex tasks in open space by astronauts [Cate95, Loft95].

Entertainment:

Constantly decreasing prices and constantly growing power of hardware has finally brought VR to the masses – it has found application in the entertainment. In last years W-Industry has successfully brought to the market networked multi-player game systems (see fig. 1.3.7.1). Beside these complicated installations, the market for home entertainment is rapidly expanding. Video game vendors like SEGA and Nintendo sell simple VR games, and there is also anincreasing variety of low-cost PC-based VR devices. Prominent examples include the Insidetrak(a simplified PC version of the Polhemus Fastrak), i-glasses! (a low cost see-through HMD) orMattel PowerGlove. Virtual reality recently went to Hollywood – Facial Waldo™ and VActor systems developed by SimGraphics allow to "sample any emotion on an actor's face and instantaneously transfer it onto the face of any cartoon character" [Dysa94]. The application field is enormous: VActor system has been used to create commercial impressive videos with ultra low cost: USD10 a second, where the today's industry standard is USD1,000 a second. Moreover, it may be used in live presentations, and might be also extended to simulate body movements

2 . VR Technology

2.1. A First Look At VR Applications: Basic Components

VR requires more resources than standard desktop systems do. Additional input and output hardware devices and special drivers for them are needed for enhanced user interaction. But we have to keep in mind that extra hardware will not create an immersive VR system. Special considerations by making a project of such systems and special software [Zyda93b] are alsorequired. First, let us have a short look at the basic components of VR immersive applications:

2.1.1. Input Devices:

Input devices determine the way a user communicates with the computer. Ideally all these devices together, should make user's environment control as intuitive and natural as possible – they should be practically invisible [Brys93e].

Unfortunately, the current state of technology is not advanced enough to support this, so naturalness may be reached in some very limited cases. In most of cases we still have to introduce some interaction metaphors that may become a difficulty for an unskilled user.

2.1.2. Output devices:

Output devices are responsible for the presentation of the virtual environment and its phenomena to the user – they contribute to the generation of an immersive feeling at most. These include visual, auditory or haptic displays. As it is the case with input, the output devices are also underdeveloped. The current state of technology does not allow to stimulate human senses in a perfect manner, because VR output devices are far from ideal: they are heavy, low quality and low-resolution. In fact most systems support visual feedback, and only some of them enhance it by audio or haptic information.

2.1.3. Software:

Beyond input and output hardware, the underlying software plays a very important role. It is responsible for the managing of I/O devices, analyzing incoming data and generating proper feedback. The difference to conventional systems is that VR devices are much more complicated than these used at the desktop – they require extremely precise handling and send large quantities of data to the system. Moreover, the whole application is time-critical and software must manage it: input data must be handled timely and the system response that is sent to the output displays must be prompt in order not to destroy the feeling of immersion.

2.2. Human

2.2. Human Factors

As virtual environments are supposed to simulate the real world, by constructing them we must have knowledge how to "fool the user's senses" [Holl95]. This problem is not a trivial task and the sufficiently good solution has not yet been found: on the one hand we must give the user a good feeling of being immersed, and on the other hand this solution must be feasible. Which senses are most significant, what are the most important stimuli and of what quality do they have to be in order to be accepted by the user?

Let us start by examining the contribution of each of the five human senses [Heil92]:

• sight................ 70 %
• hearing............. 20 %
• smell ....5 %
• touch.................4 %
• taste ....1 %

This chart shows clearly that human vision provides the most of information passed to our brain and captures most of our attention. Therefore the stimulation of the visual system plays a principal role in "fooling the senses" and has become the focus of research. The second most important sense is hearing, which is also quite often taken into consideration (see section 2.5.3 for details). Touch in general, does not play a significant role, except for precise manipulation tasks, when it becomes really essential (see section 2.3.3 and 2.5.2 for details). Smell and taste are not yet considered in most VR systems, because of their marginal role and difficulty in implementation. The other aspects cannot be forgotten too: system synchronization (i.e. synchronization of all stimuli with user's actions), which contributes mainly to simulator sickness (see section 2.2.2 for details) and finally the design issues (i.e. taking into account psychological aspects) responsible for the depth of presence in virtual environments [Slat93, Slat94].

2.2.1. Visual Perception Characterization:

As already mentioned before, visual information is the most important aspect in creating the illusion of immersion in a virtual world. Ideally we should be able to generate feedback equal to or exceeding the limits of the human visual system [Helm95]. Unfortunately today's technology is not capable to do so, hence we will have to consider many compromises and their implications on the quality of the resulting virtual environments

Position and Orientation Tracking Devices:

The absolute minimum of information that immersive VR requires, is the position and orientation of the viewer's head, needed for the proper rendering of images. Additionally other parts of body may be tracked e.g., hands – to allow interaction, chest or legs – to allow the graphical user representation etc. Three-dimensional objects have six degrees of freedom (DOF): position coordinates (x, y and z offsets) and orientation (yaw, pitch and roll angles for example). Each tracker must support this data or a subset of it [Holl95]. In general there are two kinds of trackers: those that deliver absolute data (total position/orientation values) and those that deliver relative data (i.e. a change of data from the last state). The most important properties of 6DOF trackers, to be considered for choosing the right device for the given application are [Meye92, Bhat93, Holl95]:

• Update Rate:

Defines how many measurements per second (measured in Hz) are made. Higher update rate values support smoother tracking of movements, but require more processing.

• Latency:

The amount of time (usually measured in ms) between the user's real (physical)action and the beginning of transmission of the report that represents this action. Lower

• Accuracy:

The measure of error in the reported position and orientation. Defined generally in absolute values (e.g., in mm for position, or in degrees for orientation).
Smaller values mean better accuracy.

• Resolution:

Smallest change in position and orientation that can be detected by the tracker.

Measured like accuracy in absolute values. Smaller values mean better performance.

• Range:
working volume, within which the tracker can measure position and orientation with its specified accuracy and resolution, and the angular coverage of the tracker. Beside these properties, some other aspects cannot be forgotten like the ease of use, size and weight etc. of the device. These characteristics will be further used to determine the quality and usefulness of different kinds of trackers.

Magnetic Trackers:

Magnetic trackers are the most often used tracking devices in immersive applications. They typically consist of: a static part (emitter, sometimes called a source), a number of movable parts (receivers, sometimes called sensors), and a control station unit. The assembly of emitter and receiver is very similar: they both consist of three mutually perpendicular antennae. As the antennae of the emitter are provided with current, they generate magnetic fields that are picked up by the antennae of the receiver. The receiver sends its measurements (nine values) to the control unit that calculates position and orientation of the given sensor. There are two kinds of magnetic trackers that use either alternating current (AC) or direct current (DC) to generate magnetic fields as the communication medium [Meye92].

The continuously changing magnetic field generated by AC magnetic trackers (e.g., 3Space Isotrak, Fastrak or Insidetrak from Polhemus) induces currents in coils (i.e. antennae) of the receiver (according to Maxwell's law). The bad side-effect is the induction of eddy currents in metal objects within this magnetic field. These currents generate their own magnetic fields that interfere and distort the original one, which causes inaccurate measurements. The same effect appears in vicinity of ferromagnetic objects. Under optimal conditions (lack of any kind of magnetic interference) magnetic trackers have a relatively good performance.

For illustration we give a technical description of two commonly used products – Polhemus Fastrak [Polh93] and Ascension Flock of Birds [Asce95a]:

Advantages:

- sensors are small, light and handy
- have no line-of-sight constraint
- non-sensitive to acoustic interference
- relatively high update rates and low latency
- off-the-shelf availability

Disadvantages:

- Since magnitude of magnetic field strongly decreases with distance from the emitter, the working volume of magnetic trackers is very limited and the resolution is getting worse as the emitter-receiver distance is growing.

- Magnetic field is subject to distortion, caused by metal objects inside of it (AC trackers only). Moreover, any external magnetic field generated e.g., by CRT displays or by ferromagnetic objects in vicinity (both AC and DC trackers) may cause additional distortion that leads to inaccurate measurements.

Optical Trackers:

There are many different kinds and configurations of optical trackers. Generally we can divide them into three categories [Meye92]:

• Beacon Trackers:
This approach uses a group of beacons (e.g., LEDs) and a set of cameras capturing images of beacons' pattern. Since the geometries of beacons and detectors are known, position and orientation of the tracked body can be derived [Wang90, Ward92]. There are two tracking paradigms: outside-in and inside-out

• Pattern Recognition:
These systems do not use any beacons – they determine position and orientation by comparing known patterns to the sensed ones [Meye92, Reki95].

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No fully functioning systems were developed up to now. A through-the-lens method of tracking may become a challenge for the developers [Thom94].

• Laser Ranging:

These systems transmit onto the object the laser light that is passed through a diffraction grating. A sensor analyzes the diffraction pattern on the body's surface to calculate its position and orientation. For all these systems the accuracy decreases significantly as the distance between sensors and tracked objects grows [Meye92].

Advantages:

• High update rates (up to 240Hz [Holl95]) – in most of cases limited only by the speed of the controlling computer

• Possibility of the extension to the large working volumes [Wang90, Ward92]

• Not sensible to the presence of metallic, ferromagnetic objects; not sensible to acoustic interference

• Relatively good accuracy: magnitude orders of about 1mm and 0.1°

Disadvantages:

• Line-of-sight restriction

• Ambient light and infrared radiation may influence the performance

• Expensive and very often complicated construction

• Difficulties to track more than one object in one volume

Interacting With Virtual Worlds:

The ultimate VR means that no user interface is needed at all – every interaction task should be as natural as in (real) reality. Unfortunately this is not possible today because of technical problems. However, many techniques may be used to enhance the interaction model [Bala95], but they still use some metaphors to make human-computer dialog easier.

Interaction Paradigms in 3D:

The human hand is most dexterous part of our body – in reality we use it (or both of them) intuitively to perform a variety of actions: grabbing or moving objects, typing, opening doors, precise manipulations etc. The most natural way of interacting with the computer is probably by using the hand. Therefore the majority of already introduced in section 2.3 VR input devices are coupled to our palm. They represent a broad variety of levels of advance, complexity and price, so for different applications other devices and modes of interaction are used. Basic interaction tasks in VEs are: camera control (for observation), navigation, object manipulation and information access.

• Eyeball In Hand:

With this metaphor the user has to imagine that the spaceballrepresents the eye he/she is watching the scene with. The user can intuitively translate and rotate it (full 6DOF control) to change the viewing point and direction. This metaphor is very useful when the user is immersed "inside" of the scene (i.e. the scene surrounds him/her).

• Scene in Hand:

With this metaphor the camera has the constant position and orientation, and the whole scene can be manipulated (i.e. rotated and translated). This metaphor is very useful, in the case when the user watches the whole scene (or some specific objects of it) from "outside". This is a natural way of observing from different sides the objects that appear small and therefore can be "kept in hand" (it is easier to rotate them, than to walk them around).

Navigation:

In many cases, user may want to explore the whole (very often big) environment. Walking over long distances cannot be realized so easily, because of the limited tracking range. Therefore an appropriate transport medium is needed. In general, with the help of some input devices we can define the motion of our body in virtual space. Depending on the type of application this may be either driving (in 2D space) or flying (in 3D space).

• Hand Directed:
Position and orientation of hand determines the direction of motion invirtual world. In this approach different modes can be incorporated to specify the required direction: pointing or crosshair mode. In the first case, moving is performed along a line the pointing finger determines. In the second one, a cursor (crosshair) is attached to the user's hand and the line between the eye and cursor defines the moving direction.

• Gaze Directed:
Looking direction (head orientation) specifies the line of movement. It isa relatively easy metaphor for an unskilled user but hinders "looking around" during themotion because direction of motion is always attached to the gaze direction.

• Physical Controls:
Input devices like joysticks, 3D mice, spaceballs are used tospecify the motion direction. They allow precise control, but often the lack of correspondence between device and motion may be confusing. However, construction of special devices for certain applications may increase the feeling of immersion (e.g., steering wheel for driving simulation).

• Virtual Controls:
Instead of physical devices, virtual controls can be implemented. This approach is hardware independent and therefore is much more flexible, but interaction may be difficult because of lack of haptic feedback. All these modes are based on the principle of steering a virtual vehicle through the space. The user sitting inside of this vehicle can determine not only the direction but the speed and acceleration of movements (e.g., pressing buttons, or by hand gestures). Moreover, he/she can still rotate and move his/her head in his/her local coordinate system.

The higher level navigation models can be also incorporated:

• Teleporting:
The moving through the virtual world is realized with the help of autonomous elevator-like devices or portals that once entered move the user to the specified point of space. The obvious extension of this mode is goal driven navigation, where the user can choose the target with a help of virtual menu [Jaco93] or a sensitivemap.

• World Scaling:
The distances in virtual world may be dynamically changed according tothe user's needs. For example we can scale the world down and move to the desired position (e.g., make one step one thousand kilometers long) and scale the world back to the original size. The scaling of the model up can be also performed to allow the user precise control.

Manipulation:
Once the object is selected (which is signaled by e.g., highlighting it on the screen) the user must be able to manipulate it: move, rotate, scale, change attributes etc. This can be achieved by defining special button presses, hand gestures [Stur93] or menu entries that choose a proper tool. These tools can be driven by physical input devices like mice, joysticks, sliders, gauges, hand position tracking [Ware90a] or even by a nose-gesture interface.

Information Accessing:
Nowadays, huge amounts of information are stored in computer memory and flow through computer networks. These streams of data will be growing rapidly in the near future (data highways). The real problem will be rapid retrieval and comprehensive access to the relevant information for a particular user. Standard computer interfaces are not capable to guarantee this anymore. Virtual reality with its broader input and output channels, autonomous guiding agents and space metaphors [Benf95] offers the enhancement of human perception and makes information searching

and understanding faster [Caud95, Mapl95].To make the interaction and communication with virtual worlds successful To make the interaction and communication with virtual worlds successful we cannot think just about one of previously listed interaction techniques. For each application area, other subset of them will be needed to guarantee the optimal performance. Ideally, not only software but also hardware should be transparent to the user and should provide maximum freedom and naturalness. To achieve this, however, both refinement of hardware devices and software paradigms for interaction are necessary.

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