VR Input devices

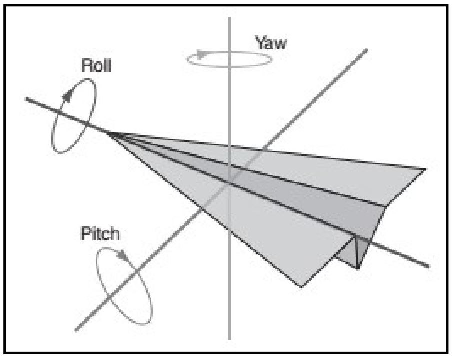
VR input devices are the physical devices that convey information into the application and support interaction in the Virtual Environment. Different types of VR input devices are listed below following a brief discussion.

1. Three-dimensional position trackers
   i. Mechanical trackers
   ii. Electromagnetic trackers
   iii. Ultrasonic trackers
   iv. Infrared trackers
   v. Inertial trackers
2. Navigation and manipulation interfaces
   i. Wayfinding
   ii. Travel
   iii. Trackballs
3. Gesture Interfaces
   Pinch Gloves
   5DT Data Glove

1. Three-dimensional position trackers

Tracking devices allow a VR system to monitor the position and orientation of selected body parts of a user. Many interaction devices incorporate a tracking device of some sort in order to measure the position and orientation of the body part they are attached to. In tracking devices, such as Head Mounted Display(HMD), the position and orientation of the head is measured. Attached to a glove, a tracking device measures the position and orientation of a hand. Based on this information, the hand can be rendered in the virtual world at the same position with respect to the user, providing feedback that is often necessary for dexterous manipulation.

Tracking devices, also called 6-degree-of-freedom (6DOF) devices, work by measuring the position (x, y, and z coordinates) and the orientation or angles of rotation in three dimensions with respect to a reference point or state. These angles of rotations are also known as yaw, pitch, and roll (as shown in the figure below).



In terms of hardware, the following three components are required:

- A source that generates a signal.
- A sensor that receives the signal.
- A control box that processes the signal and communicates with the computer.

Depending on the technology used, either the source or the sensor is attached to the body, with the other placed at a fixed spot in the environment, serving as a reference point. Most types of virtual reality interaction devices will have a tracker on them. The special purpose hardware used in virtual reality to measure the real-time change in a 3D object position and orientation is called a tracker. When designing or evaluating a virtual reality system that will receive tracking information, it is important to pay attention to the performance parameters. Some important performance parameters are outlined below.

Performance parameters of modern VR trackers are:

- **Latency** (lag) - represents the time gap between the change in the objects position and/or the orientation and the time when the attached sensors detect this change.
- **Update rate** - is the number of measurements per second reported by the tracker.
- **Resolution** - ability to display fines details of the object in the scene.
- **Accuracy of the tracking system** - the difference between the object's actual 3D position and measurements reported by the tracker.

6DOF tracking devices come in several basic types of technology: Mechanical, Electromagnetic, Ultrasonic, Infrared (IR), and Inertial.

i. Mechanical trackers

A mechanical tracker was the first tracker used in a VR simulation. A mechanical tracker is similar to a robot arm and consists of a jointed structure with rigid links, a supporting base, and an "active end" that is attached to the body part being tracked, often the hand.

Advantages:

- Fast and accurate compare to many other tracker technologies.
- These trackers have low jitter and latency rates compare to others.
- These are immune to interference from magnetic fields and provide consistent accuracy.

Limitations:

- It tends to encumber the movement of the user.
- Technical problem of tracking the head and two hands at the same time is still difficult.
- If the links are longer, weight and inertia increases that leads to unwanted mechanical oscillations.
- Problems of fatigue and diminish sense is also observed in cases where the structure of tracker is supported by users.

ii. Electromagnetic trackers

The user requirement for 3D measurement requires the user's freedom of motion in the process of tracking. This has led to the development of noncontact 3D measurement devices called electromagnetic trackers, or more commonly magnetic trackers. An electromagnetic tracker allows several body parts to be tracked simultaneously and will function correctly, if objects come between the source and the detector. These types of trackers are noncontact measurement devices that uses magnetic field produced by a stationary transmitter to determine the real-time position of moving receiver.

Advantages:

- Several body parts can be tracked simultaneously.
- They do not require line of sight to the tracked object.

Limitations:

- They are affected by large amounts of metal and become inaccurate at times.
- They suffer from latency problems, distortion of data.
- The detector must be within a restricted range from the source. Hence the user has a limited working volume.

iii. Ultrasonic trackers

An ultrasonic tracker is a noncontact position measurement device. It uses an ultrasonic signal produced by a stationary transmitter to determine the real-time position of a moving receiver element. Ultrasonic tracking devices consist of three high frequency sound wave emitters in a rigid formation that form the source for three receivers that are also in a rigid arrangement on the user.

Advantages:

- They are not affected by large amounts of metal like magnetic trackers.

Limitations:

- They have a restricted workspace volume.
- They must have a direct line-of-sight from the emitter to the detector.
- They are affected by temperature and pressure changes, and the humidity level of the work environment.

iv. Infrared trackers

IR (optical) trackers are a class of optical tracker, which is a noncontact measurement device that uses optical sensing to determine the real-time position or orientation of the object. It utilizes several emitters fixed in a rigid arrangement while cameras or "quad cells" receive the IR light. To fix the position of the tracker, a computer must triangulate a position based on the data from the cameras.

Advantages:

- This type of tracker is not affected by large amounts of metal
- It has a high update rate, and low latency.

Limitations:

- The emitters must be directly in the line-of-sight of the cameras or quad cells.
- Any other sources of IR light, high-intensity light, or other glare will affect the correctness of the measurement.

v. Inertial trackers

Inertial trackers are self-contained sensors that measure the rate of change in an object orientation and object translation velocity. There are several types of inertial tracking devices that allow the user to move about in a comparatively large working volume, because there is no hardware or cabling between a computer and the tracker.

Advantages:

- Less hardware is required to implement these types of tracking.
- There is very little lag between movement of the sensor and the reported movement.

Limitations:

- They only report relative movements, not absolute positions.
- Because of the lack of a fixed reference, the reported values accumulate error.

2. Navigation and manipulation interfaces

Navigation and manipulation interfaces are key components of any VR system. Manipulation tasks involve selecting and moving an object. Users need to be able to manipulate virtual objects. Sometimes, rotation of the object is involved as well. These devices permit the interactive change of the view, allows exploration, selection and manipulation of a virtual object of interest in the virtual environment. Integrated within a structure that houses user-programmable pushbuttons, trackers become navigation and manipulation interfaces. Navigation tasks have two components-wayfinding and travel.

i. Wayfinding

Wayfinding refers to finding and setting routes to get to a travel goal within the virtual environment. Wayfinding in virtual space is different and more difficult to do than in the real world, because synthetic environments are often missing perceptual cues and movement constraints. It can be supported using user-centered techniques such as using a larger field of view and supplying motion cues, or environment-centered techniques like structural organization and wayfinding principles.

ii.Travel

Travel involves moving from the current location to the desired point. Good travel techniques allow the user to easily move through the environment.

There are three types of travel tasks:

- ✓ Exploration
- ✓ Search
- ✓ Maneuvering.

Travel techniques can be classified into the following five categories:

- Physical movement - user moves through the virtual world
- Manual viewpoint manipulation - use hand motions to achieve movement
- Steering - direction specification
- Target-based travel - destination specification
- Route planning - path specification

iii.Trackballs

Trackballs are interface that allows navigation and manipulation in relative coordinates. One such example is trackball such as Logitech Magellan (shown in the below figure).

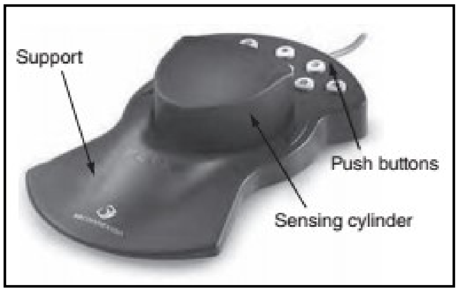


Figure: Logitech Magellan track ball

It is a sensorized cylinder that measures force and torque applied by the user's hand. On application of force or torque, output is measured and sent to the computer. Push buttons are programmed according to application and can be switched on/of by users' finger. Trackballs suffer from sensor coupling. Sometimes a user may want to have a VR object translate but not rotate. But, the VR object exhibits both translation and rotation.

3.Gesture interfaces

Gesture interfaces are devices that measure the real-time position of the user's fingers or wrists in order to allow natural gesture-based interaction with the environment. Gesture recognition enables humans to interface with the machine (Human Machine Interface) and interact naturally without any mechanical devices. Using the concept of gesture recognition, it is possible to point a finger at the computer screen so that the cursor will move accordingly. This could potentially make conventional input devices such as mouse, keyboards, and even touch-screens redundant. It allows additional degrees of freedom by sensing individual finger motion. Gesture recognition is useful for processing information from humans, which is not conveyed through speech or type.

i. Pinch Gloves


Figure: A Pinch Glove

Pinch Gloves by Fakespace (Shown in the figure) are considered to be the world's one of the most widely used virtual manipulation device. It enables users to "pinch" and "grab" virtual objects or initiate some action. Pinch gloves allows each finger to be programmed differently to generate different actions as desired by the user. Pinch Glove Systems are reliable and offer a low cost method for recognizing natural gestures.

Advantages:

- The Pinch glove is preferred for its simplicity in design and operation.
- Does not need calibration.
- Allows use of both hands for gesture interaction.
- Enables confirmation of gestures though the hand haptic sensing.

Disadvantages:

- The glove has limited capability to detect whether a contact is made or not, and cannot measure intermediary finger configurations of the virtual hands.
- Often the virtual hands are unable to track the true position of the user's fingers in real time leading to less realism.

ii. 5DT Data Glove

5DT Data Glove Ultra is recognized as a hand data motion capturing method for animation and virtual reality. The system can communicate with the computer via a USB cable or wireless connection. A serial port (RS 232 – platform independent) option is available through the 5DT Data Glove. Ultra Serial Interface Kit is also available featuring 10-bit flexure resolution, great comfort, low drift, and support to open architecture

Advantages:

- High data quality
- Low cross-correlation
- High data rate

Digiglove and CyberGlove are other important sensing gloves available for VR environment.

Graphics Display Interfaces

Graphics Display is a computer interface that is designed to present synthetic world images to the users interacting with the virtual environment.

The important factors which make a simulated world more realistic for the user are:

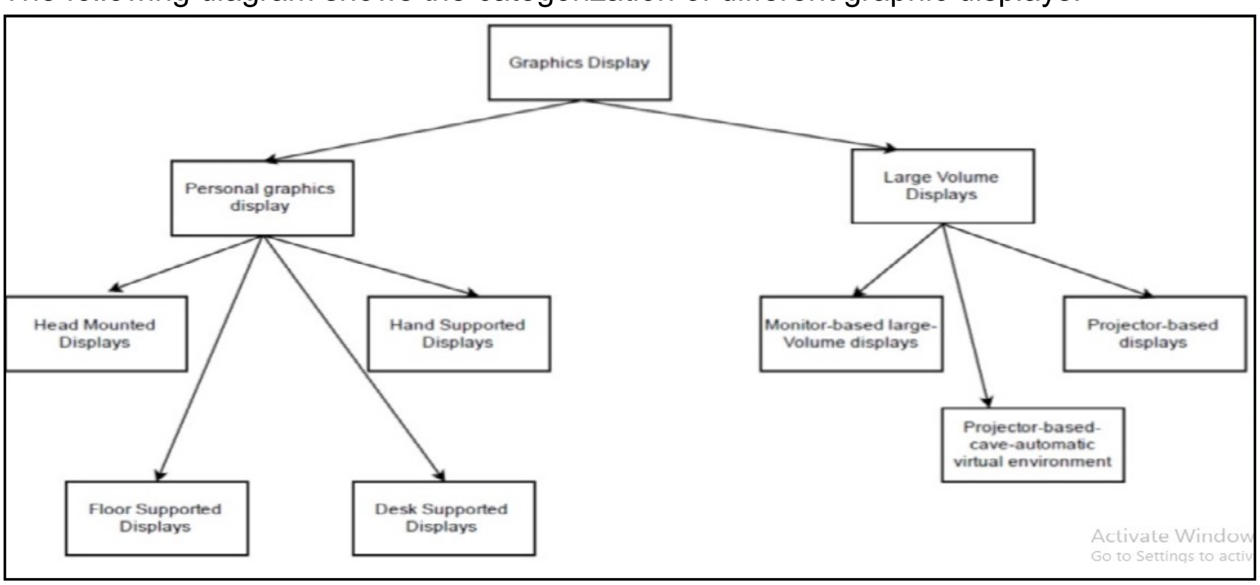
- Depth perception
- Large viewing area
- High-resolution images

Graphics displays, displays with tracked stereo glasses, autosterioscopic (glassless) displays, multi projector screen systems, together with sound display systems are important class of output devices in a virtual environment.

The following display characteristics are the important considerations while choosing a product for visual interaction in VR environment:

- Type of image
- Image resolution
- Display technology
- Field of view

The following diagram shows the categorization of different graphic displays:



1. Personal graphics display

A graphics display that outputs a virtual scene destined to be viewed by a single user is called a personal graphics display. The type of image produced may be monoscopic or stereoscopic, monocular (for single eye) or binocular (displayed on both eye).

Examples: The following are some examples for personal graphic displays

i. Head-mounted displays
ii. Hand-supported displays
iii. Floor-supported displays
iv. Desk supported displays/Autostereoscopic monitors

i.Head-mounted display (HMD)

A HMD is a display device that is worn on the head or can be integrated as part of a helmet with a small display optic in front of the eyes. HMD can focus at short distances and project an image floating about some 1–5 m using special optics placed between the HMD small image panels and the user's eyes. The diagram shows a HMD by Sony (Model HMZ T2).

HMD that produces image for single eye is called monocular HMD and those that produce image for each eye is known as binocular HMD. A recent variant called optical head-mounted display (OHMD), are a class of wearable display that has the capability of reflecting projected images and also allowing the user to see through it.

Today HMDs come with different capabilities. Some HMDs can display just a computer generated image (CGI), while some can show live images from the real world and some display combination of both. Image is purely a virtual image when seen with those displaying computer-generated image.

HMDs that superimpose real-world view with CGI lead to augmented reality or mixed reality. One way to produce augmented reality is by projection of CGI through a partially reflective mirror and viewing the real world directly. This method is known as Optical See-Through. Another method of achieving augmented reality is by accepting video from a camera and mixing it electronically with CGI. This method is known as Video See-Through. The HMDs are designed to ensure that no matter in what direction a user might look, the monitor stays in front of his/her eyes. HMDs have a screen for each eye that gives the perception of depth into the images looked through it.

HMDs can be divided into two categories depending on the display technology used in them. They are:

- HMD with liquid crystal display(LCD)
- HMD with Cathode Ray Tube(CRT) display

The following table gives a comparison in these two types of HMDs

HMDs with LCD	HMDs with CRT
More compact, lightweight	Bulky and heavy
More efficient	Less efficient
Cheaper than CRT	Costly
	Better screen resolution and brightness
Used for consumer grade devices	Used in expensive professional based devices for VR interaction

HMDs find enormous applications in the following fields:

- Aviation
- Engineering
- Science and medicine
- Gaming and video applications
- Sports and training and simulations.

ii.Hand-supported displays (HSDs)

These are another type personal graphics displays wherein a user can hold it in one or both hands in order to periodically view a synthetic scene. This allows user to go in and out of the simulation environment as demanded by the application.

HSDs have additional feature namely push buttons that can be used to interact with the virtual scene. HSD and HMD both use special optics to project a virtual image in front of the user.

An example of popularly used HSD is NVIS Virtual Binocular SX shown in the figure.

It offers improved immersive display combining high-resolution micro displays with adjustable, wide field-of-view optics similar to that of a pair of binoculars.

iii.Floor-supported displays

Floor-supported displays are alternatives to HMDs and HSDs in which an articulated mechanical arm is available to offload the weight of the graphics display from the user. Most, floor-supported displays are known for their capability to integrate sensors directly into the mechanical support structure holding the display. Floor-supported displays with six sensors can determine the position and orientation of the end of the supporting arm

relative to its base.

Some important characteristics include high accuracy, lower latency and lower orientation error .They offer larger fields of view and better graphics resolution compared to HMDs or hand-supported displays.

An example of floor-supported display is Boom3C by Fakespace Labs shown in the figure.

iv. Desk- supported displays

Desk-supported displays overcomes the problem faced by users due to the excessive display weights in HMDs and HSDs. Floor-supported display system also suffer from problem of oscillation due to excessive weight. Desk-supported display is an alternative to weight problem.

These are fixed and designed to be used for viewing with user in sitting position. User can't move freely compared to HMDs or HSDs. Desk-supported displays include auto stereoscopic category displays, which can produce the stereo-pair images simultaneously on a single panel that can be viewed with unaided eyes. It does not require two display panels. Auto stereoscopic display uses a special "column-interlaced" image format, which alternatively presents specific columns assigned to the left and the right-eye view, respectively. Since each eye effectively sees only its corresponding image columns, it results in the perception of two images, which through parallax, provides a single stereo image floating in front of the users. Auto stereoscopic displays can be of two types- passive and active auto-stereoscopic displays. Passive auto-stereoscopic displays do not track user's head and thus restrict user's position; but active auto-stereoscopic displays track the head motion and give more freedom of motion.

Some of the disadvantages of desk-supported display include

- ***Reduced horizontal image resolution*** - half of the columns display image for one eye and half the image of the other eye.
- ***Increased system complexity*** – It requires added illumination optics and/or dedicated hardware integrated within the display.
- ***Increased cost*** compared to others such as CRT or flat panel displays of same size.

Despite these shortfalls, an important advantage of these graphics display is their ability to present a stereo image without requiring the user to wear any vision apparatus.

Large volume displays

Another class of graphics displays called large volume displays are used in VR environment that allow more than one user located in close proximity to simultaneously view a stereo or monoscopic image of the virtual world.

Different types of large-volume displays are:

i. Monitor-based large-volume displays
ii. Projector-based large-volume displays
iii. Projector-based-cave-automatic virtual environment

This classification is largely based on the type and size of display being used. Monitor-based displays include one or side-by-side arranged CRTs while projector-based include workbenches, CAVEs, display walls, and domes.

Large volume display offers user with larger work envelope, thus improving upon user's freedom of motion and ability of natural interaction compared to personal displays.

These displays are based on temporal-interlaced graphics format that display alternating stereo-pair images in rapid succession.

i. Monitor-based large-volume displays

This display relies on use of active glasses coupled with stereo-ready monitor. The user of the system looks at the monitor through a set of shutter glasses. The stereo-ready monitors are capable of refreshing the screen at double of the normal scan rate. In principle the computer sends two alternating but slightly offset images to the monitor. The active glasses are synchronized and connected to an IR emitter located on top of the CRT display in a wireless mode. The IR controller controls and signals orthochromatic liquid crystal shutters to close and occlude the eyes alternately. The brain registers this rapid sequence of right- and left-eye images and fuses them to give the feel of 3D.

Advantages - Images are sharper than that of LCD-based HMDs, thus preserving the resolution of the CRT and offer nearly flicker free image. Even prolonged use of simulation does not result in fatigue and tiredness.

Limitation - Images do not change to reflect change in the user's viewing angle.

ii. Projector-based displays

Contrary to personal graphics displays that allow single user, projector-based displays have advantage of allowing group of closely located users to participate in a VR simulation. A high resolution stereo-pair image (typically 1280 × 1024) at 120 Hz is produced by CRT projectors using three tubes (R, G, B). Recently digital projectors have replaced CRT projectors with better luminance capability. The stereo projector operating in frame sequential mode splits the scan lines of the image into two components which are then viewed by the user through active glasses refreshed at 60 Hz. Although use of projector based displays are a better way to immersive feel in the environment but need high setup cost and also fall short to project bright images. Presence of ambient light has adverse effect on viewing luminance. When digital projectors are used against CRT projectors, the problem of low luminance is resolved to a greater extent due to their higher order-of-magnitude in luminance.

iii. Projector-based-Cave-Automatic Virtual Environment

A Cave-Automatic Virtual Environment (CAVE) is a projection-based VR display that uses tracked stereo glasses to feel the environment. CAVE is basically a small room or cubicle, where at least three walls (and sometimes the floor and ceiling) act as giant monitors. The display gives the user a very wide field of view, something that most

HMDs cannot do. Users can also move around in a CAVE system without being tethered to a computer, though they still must wear a pair of goggles that are similar to 3D glasses.

The active walls are actually rear-projection screens. A computer provides the images projected on each screen, creating a cohesive virtual environment. The projected images are in a stereoscopic format and are projected in a fast alternating pattern. The lenses in the user's goggles have shutters that open and shut in synchronization with the alternating images, providing the user with the illusion of depth. Tracking devices attached to the glasses tell the computer how to adjust the projected images as you walk around the environment. Users normally carry a controller wand in order to interact with virtual objects or navigate through parts of the environment. More than one user can be in a CAVE at the same time, though only the user wearing the tracking device will be able to adjust the point of view. All other users are mere passive observers.

CAVE has big benefits over many other forms of display including HMDs especially for scientific and engineering applications. Multiple people can share the VR experience together with because CAVE makes use of large and fixed screens that are more distant from the viewer. This minimizes the hindrances carried or worn by users thus giving better flexibility in movement and interaction.

Sound display and interface

A VR system is greatly enhanced by the inclusion of an audio or sound component. Sound displays are often used to communicate important information in video games. Essentially, Sound displays are nothing but the synthetic sound feedback for users interacting in the virtual world. The sound can be classified into

Monoaural - When both ears hear the same sound it is called monoaural sound.

Binaural - When each ear hears a different sound it is called binaural sound.

Sound displays together with graphics displays greatly increase the simulation realism. It can improve the user's interactivity, immersion, and quality of the perceived image. Sound display may produce mono, stereo, or 3D audio.

Mono sound: The evolution of 3D sound can be traced through time and technology starting with monophonic sound. Mono sends one signal to every speaker. It appears that all the sounds of the environment are coming from each individual speaker. If there is only one speaker, then all the sounds seem to be coming from that point.

Stereo sound: A stereophonic sound is the next step in the development of realistic sound production. Stereo sound when heard using headphones seems to originate inside the user's head. It allows for the sounds to seem as if they are coming from anywhere between two speakers. This is accomplished by delaying the signals between the two speakers by a few microseconds. The smaller the delay, the closer to the center the source appears to be located. When using simple stereo headphones, the source would appear to move with the head motion.

3D surround sound: A high performance immersive virtual reality environment is achieved when graphics feedback is accompanied with 3D sound, also known as virtual or surround sound. A 3D surround sound, used in many theaters, uses the idea of stereo but with more speakers. The sound is set so that a sound seems to move from behind the listener to in front of the listener. In practical scenarios, users in a room receive mix of original sound and sound that is reflected off the walls, the floor, and the ceiling, adding to the direct sound received from the source.

Examples of input devices

VR requires a special set of user input tools. There are examples of input devices that have been developed for use with virtual reality.

Glove, DataGlove, and PowerGlove

A glove device is designed specifically for capturing the movement and location of the hand in order to explore and manipulate objects. When we move our hand, the glove picks up the movement and sends an electrical signal to the computer that translates the movement from the real space into the virtual space. Often, we are able to see our virtual hand in the virtual world. This greatly aids in the hand–eye coordination, necessary for any kind of positioning in a 3D world.

A DataGlove is made of lightweight lycra that consists of two measurement tools. The first tool measures the flex and extension of every finger. It does so by using a set of fiber-optic cables that run along each finger, with a photo-sensor at one end and a LED at the other end. When a person wears a glove and bends a finger, light from the LED escapes through small holes in the cable's sheath. Thus less light reaches the photo-sensor and generates a weaker electrical signal. In this way, the computer receives input about which fingers are bent, and by how much. The second tool measures the absolute position (x, y, and z axes) and the orientation (roll, pitch, and yaw) of the hand. This tool has two parts: a stationary transmitter and a receiver, which are placed on the glove. By measuring the electrical charges in transmitter and receiver one can calculate the position and orientation of the glove. This system is known as the Polhemus magnetic positioning system. One problem with the DataGlove is that it requires recalibration for each user, as it is very sensitive to knuckle position.

A PowerGlove is a low-cost version of DataGlove that performs the same functions using completely different methods. For flex-measuring, the PowerGlove has a strip of mylar plastic coated with electrically conductive link. This strip is placed along each finger and when a finger is flexed, the electrical resistance changes. The change corresponds to the degree bent. For absolute position and orientation, the PowerGlove uses the simpler ultrasonic positioning technique. Receivers pick up the signals from two ultrasonic transmitters on the glove and translate them into a position in space.

PowerGlove is less accurate than the DataGlove. But PowerGlove is easier to use than the DataGlove.

Dexterous hand master (DHM)

A dexterous hand master (DHM) is an exoskeleton that is attached to the fingers using velcro straps, and attached to each finger joint is a device called a hall effect sensor, whose purpose is to measure the finger-join angle. Instead of using optical or electrical signals, a DHM uses mechanical linkages to track the movement of the hand. DHM is more accurate than a PowerGlove or a DataGlove, It also measures the side-to-side motion of each finger. In addition, it takes into account the fact that a human finger has three sections, rather than two, which the DataGlove and PowerGlove are capable of measuring. This precision makes it extremely useful for any application that requires a high level of control, such as controlling dexterous robotic hands. DHMs are also less sensitive than either a DataGlove or a PowerGlove with respect to different hand sizes and placement on the fingers. However, a DHM is rather clunky to work with.

Mouse and joysticks

Mouse and joysticks are popular input devices for a computer system. They are sufficient for navigating around a simple virtual world in two dimensions and for performing simple tasks by using the buttons on the devices. Mouse and joysticks usually have two degrees of freedom, although there are mouse designed with six degrees of freedom. Ultrasonic, electromagnetic, or gyroscopic tracking is used for such a six-degree (or 6D) mouse.

Wands

A wand is like a joystick with an unrestrictive base that has 6DOF. There are buttons on a wand, and a thumbwheel that allows scalable values to be entered. In a virtual world, a wand does not necessarily have to appear as a pointing device. It can be represented as a drill, paintbrush, spray gun, or even an ice-cream cone. One of the strengths of virtual environments is that the appearance of an object can be whatever the designer chooses—it needs bear no resemblance to the object's physical appearance. A wand is very easy and intuitive to use. Regardless of its representation in the virtual world, most of the actions involve just "point and click" with the wand.

Force (space) balls

A force ball has a ball that you could apply force on, though you cannot actually move the ball. The force you apply is picked up by sensors in the center of the ball, from where the information is then relayed to the computer. A force ball has 6DOF.

Advantages:

- Easy and comfortable to use
- It requires very little space as there is no movement.
- No need to hold it in the midair, as user would use a 6D mouse.
- Most force balls have programmable buttons for a developer to configure to suit the needs of the application

Limitations:

- Uses of a force ball are limited to navigation and selection.
- It is not suitable for interactions or issuing commands.

Biological input sensors

Biological input sensors use dermal electrodes to detect a particular muscle activity. For example, they can be placed near the eyes so that by making simple eye movements, you can navigate through the virtual worlds. It is also possible that, in the future, we can detect a hand movement by wearing a bracelet that can detect hand muscle activities, thereby replacing a more cumbersome glove.

Biosensors are a neural interface technology that detect nerve and muscle activity. Currently, biosensors are used in measuring muscle electrical activity, brain electrical activity, and eye movement.

Haptic Feedback

Haptic feedback is the use of touch to communicate with users. Haptic technology refers to technology that interfaces to the user via the sense of touch by applying forces, vibrations, and motions to the user.

Physical interfaces are expensive to implement, and difficult to reconfigure to match different user requirements and applications. The main disadvantage of an interface based on 3D models is the absence of physical feedback. “Feeling” a control tool is essential; otherwise the manipulation requires too much effort and becomes imprecise. Haptic technologies aim at solving this problem by enabling virtual objects to provide a tangible feedback to the user. Haptic technology can be used in creating and controlling of virtual objects. Haptic interfaces essentially convey vital sensorial information to their users and help them to gain tactile identification of virtual objects in the environment and allow them to move these objects to perform a task. Haptic feedback has significantly improved the simulation realism when added to visual and 3D sound for the users of the VR environment.

Haptic interfaces deal with both touch and force feedbacks. Information such as contact surface geometry, surface roughness, slippage, and temperature are conveyed by touch feedback but do not resist users from moving through virtual surfaces or other contact motions. Force feedback on the other hand provides real-time information about weight and inertia of the virtual objects and also about the surface compliance. Force feedback has ability to actively resist the user’s contact motion and can even bring to a halt for large feedback forces.

This emerging technology promises to have wide-reaching applications. For example, haptic technology has made it possible to investigate, in detail, how the human sense of touch works by allowing the creation of carefully controlled haptic virtual objects. These objects are used to systematically probe human haptic capabilities that would otherwise be difficult to achieve. Popular haptic interface include Cyberforce, Omega, Delta, Spidar, and HapticMaster.

Tactile and force feedback interfaces

Temperature, size, shape, firmness, and texture are some of the bits of information gained through the sense of touch. Tactile feedback deals with how a virtual object feels. Tactile feedback are available for hand devices and skin interface. Products like CyberTouch Glove provides vibrotactile feedback to the user while temperature feedback glove allows users to detect thermal characteristics (such as temperature, thermal conductivity, and diffusivity) of the virtual object and help them to identify material of the virtual object.

Examples of tactile feedback devices include Tele Tact Glove (the UK’s Advanced Robotics Research Centre and Airmuscle), Begej Glove Controller (Begej Corp.), TiNi Alloy Tactile Feedback System, and Sandpaper System from MIT.

Force feedback deals with how the virtual environment affects a user. There are several types of devices that allow a user to “feel” certain aspects of the virtual environment. Motion platforms for simulators and simulated rides, force feedback gloves, exoskeletons, and butlers are all forms of force feedback. When compared to tactile feedback interface, the force feedback interfaces need larger actuators, heavier structures, larger complexity, and come at greater cost. Force feedback interfaces have better mechanical bandwidth but need to be firmly attached on some supportive structures to avoid unwanted slippage and accidents. Some of well received force feedback interfaces include non-portable devices including joysticks (as shown in the figure) and haptic arms and portable interfaces, such as force feedback gloves.

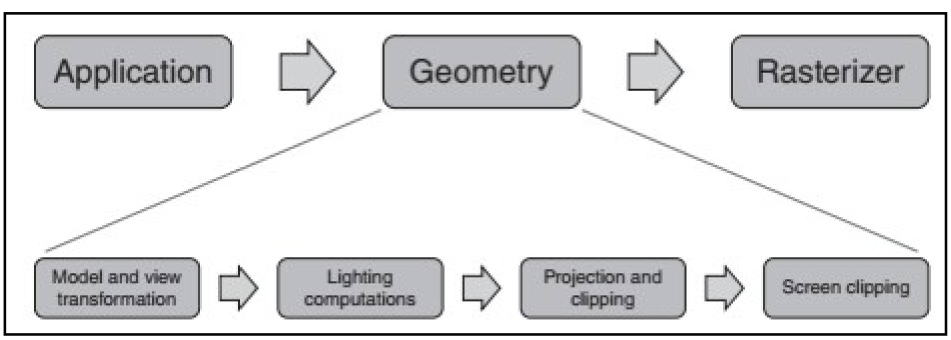
Graphical rendering pipeline

Rendering is an important phenomenon for visualization in graphics and virtual reality. In generic terms rendering deals with generating 2D scene from given 3D geometrical models of the objects of the world (or virtual world). Pipelining supports parallelism to speed up processing. Graphics rendering pipelining is essentially dividing rendering tasks into multiple stages and assigning them to different hardware resources.

Graphics rending pipeline (as shown in the figure) has three conceptual stages:

- Application
- Geometry
- Rasterizer.

These stages are further divided into sub stages that are associated with specific task in the rendering process. Each stage can be pipelined or parallelized and the slowest stage of the pipeline determines the graphics performance.



1. Application stage

This is the first stage of the graphics pipeline that reads user mediated input devices and performs changes to the coordinates of the virtual camera to reflect change in the orientation of virtual objects. Haptic input devices such as trackballs and sensing gloves are used at this stage to acquire input. This stage is implemented entirely in software by the CPU and handles collision detection and response based on properties of virtual object for haptic interfaces including force feedbacks. Application stage also deals with optimization tasks including reduced object model complexity and use of reduced floating point precision wherever possible. Optimized models with less number of polygons means—less to feed down the pipe. Use of single point precision and minimum number of divisions will lead to more optimized rendering performances. Since all is done in CPU, super scalar architecture can be used to achieve best performance.

2. Geometry stage

From the higher perspective, it is the second stage and important in the graphics rendering pipeline. It is divided into sub stages namely:

i. Model and view transformations
ii. Lighting computation
iii. Projection and Clipping
iv. Screen mapping.

The functions of each sub stage are described below.

i. Model and view transformations:

Model transformation links object coordinates to world coordinates and any change in the model transform allows the several instances of the same object in the scene. Model transformation includes translation, rotation, scaling etc. The viewing transformation transforms objects from world coordinates to camera coordinates (eye space). It captures the position and orientation of the virtual camera in the virtual world.

ii. Lighting computations:

This sub stage computes shading and texturing details of the object model which makes the scene more realistic. The physical realism is achieved by computing vertex color of the object that is based on many parameters including the use of type and number of simulated light sources, the lighting model and the material properties of the surface. Atmospheric effects such as fog or smoke is also considered wherever present. Optimization can be achieved at this sub stage by using simple lighting model and using fewer light source wherever possible. Use of fewer light in the scene will takes less time. A simpler shading model has less computations but at the cost of less realism.

iii. Projection and clipping:

This stage determines what portion (volume) of the virtual world the camera actually sees. There are two projection techniques:

- Parallel projection
- Perspective projection

Front and back "clipping planes" determines the restricted view of the portion of the virtual world as seen by the camera at a given time. The rendering pipe receives what is within the viewing cone also called frustum. Projection transformation transforms the view volume to normalized view volume and performs orthogonal projection.

Clipping transformation ensures that only objects inside the viewing frustum are rendered. Objects that are partially inside are clipped by applying suitable 3D clipping algorithm.

iv. Screen mapping:

Screen mapping, also known as viewport transformation renders scene or canonical view volume to the pixel coordinates of the screen (window with corners). Note that screen mapping is essentially a translation followed by a scaling that affects the x and y coordinates of the primitives (objects), but not their z coordinates. Virtual object that are described using lower order polygons such as triangle will be rendered faster than those described using high order polygon (quadrangle etc.). Therefore, optimizing can be done by determining the way the surfaces are described. Note that low order polygonal surface definitions may bring restriction on shading and texturing details in some cases.

3 .Rasterizer stage

This stage converts vertices information from the geometry stage (x, y, z, color, texture) into pixel information on the screen. This stage approximates primitives into pixels and determines which pixel to turn on. It would also interpolate values across primitives (colors, normals, position at vertices) if required. The pixel information such as color is obtained from color buffer while pixel z-vale is obtained from z-buffer which is of the same size as of color buffer. Rasterizer stage assures that the primitives that are visible from the camera view are displayed. Process called "double buffering" is used for flicker free display. In this a virtual scene is rendered first in the back buffer then swapped with the front buffer. The front buffer stores the recent image being displayed. Together all the buffers on the system form the frame buffer. Operations at this stage are performed in hardware to achieve speed.

Applications of Virtual Reality

The scope for the useful application of the VR technology is vast. The following are some aspects of VR applications.

1. Art and entertainment

Virtual reality can be used as a novel medium to create interactive and surrealistic art forms. It can also be used as an instrument that takes the user on a guided tour of existing conventional art forms like paintings, music, and moving pictures. Its art will let users experience fantasies that have been the stuff of science fiction to date. Games play an important role in the entertainment and development of human–machine interfaces and the introduction of I/O devices to the public. These games have used VR to a large extent for user engagement and improve the sense of presence in the scene. Adventure and video games have evolved over last two decades significantly that put a considerable impact on development of VR-enabled hardware and software. Immersive games allow the user to participate in the battle or explore the jungle as if it is realty.

2. Education

Virtual reality has emerged as a powerful tool for education, since people grasp images much faster than lines of text or columns of numbers. An active participation in the learning process is critical to learning for better results. Virtual reality offers multisensory immersive environments that engage students and allow them to visualize information in much better, accurate, and interesting way.

The following areas are benefited by applying VR in education.

Training and simulation

The most sensible and practical use of VR is found in training through simulations. Training is often very costly or dangerous in many cases. VR simulators are helpful for training in such cases. It allows construction variety of training scenarios, testing them, and even allows alteration for change that could not have been possible in practical situations. The high-end flight simulators have been used for military and commercial flight instruction. The simulator allows the pilot to become familiar with a new plane before he must fly it for real. It also allows the pilot to practice emergency procedures that would be too dangerous in real life. Distributed simulations allow users in remote locations to participate in the same environment. Training tools can also be used for common citizens. For example, virtual cars could be used for driving training to reduce the expense of cars, minimize accidents and insurance costs.

Classroom teaching

Virtual reality tools can be used for increased student–teacher participation in the learning process in the classroom. Classroom activities, such as hands-on learning, group projects and discussions, field trips, and concept visualization, can be better experienced using VR tools compared to traditional teaching methods, involving text, oral, and screen-based presentations that do not use a human's full capacity to learn. VR is all about natural interaction with information with sense of real-time interaction with the data sources. Instead of reading about foreign places or watching a videotaped program, students can explore new worlds such as foreign countries, ancient times, or the human body. VR offers a learning experience that many children and adults find interesting, thus giving motivation to learn. It is extremely useful for teaching basic mathematics and way of living by the active participation of the student as an active object in the virtual world.

Virtual classroom

Concept of virtual classrooms can be implemented using telepresence, where students are not limited to classes that are taught at their school, in their town, or even in their nation. Teleconferencing has allowed for persons at different locations to form a virtual classroom with active classroom discussions. Telepresence allows remote students to work together on group projects that are an important part of class participation and learning. Users may be given the ability to effect the remote location. In this case, the user's position, movements, actions, voice, etc., may be sensed, transmitted, and duplicated in the remote location to bring about this effect. Therefore, information may be travelling in both directions between the user and the remote location.

Abstract representation and visualization

Virtual reality provides the tools to visualize and manipulate abstract information, thus making it easier to understand. For example, flows of power and data communications traffic can be visualized dynamically in three dimensions. Virtual environments can allow participants to experiment with physics concepts such as a virtual physics lab that allows students to control gravity, friction, and time. The advanced input sensors of VR can be used for motion analysis and modeling, rehabilitation, and physical therapy. Motion analysis can help in training athletes to prevent them from injuries and improve their performance.

3. Manufacturing and architecture

Virtual reality has contributed immensely to the field of architecture and CAD/CAM-based projects. It offers the potential to enhance architecture by combining 3D design, HMDs, sound, and movement to simulate a walkthrough of a virtual space before an expensive construction on an actual physical structure begins. Flaws in a design and their impact can be studied for saving cost of redesign and modifications. It also allows the client to visualize structures what they are about to build. Walking through virtual environments provides an opportunity to test the design of buildings, interiors, and landscaping, resolve misunderstandings, and explore options. Complex objects can be moved and altered without much hassle to simulate real conditions such as the shadows cast by the movement of a light source. External factors, such as impact of sunlight and orientation of the structure, can be modified to achieve optimal natural effect through the use of HMDs, 3D sound, and mechanisms for navigating through the space and contribute to the illusion of moving through a real structure.

4. Science

Scientists generate hypotheses based on analysis of plenty of data that come from events that are inherently 3D. VR technologies enable scientists and technologists to visualize data in not only two-dimensional (2D) but also 3D world coordinate system such as visual impact of 3D equations, 3D models of genes, and many more. VR also helps researchers create interactive simulations of scientific phenomena. VR is a new and effective tool for studies and researches in science for studying complex concepts like zero gravity with experience. A virtual-physics laboratory is an alternative to a physical laboratory where users are allowed to conduct simple experiments. In this artificial environment, it is easy to see the effects of gravity without any interference of friction.

5. Medicine and surgery

Medical diagnostic centers and hospitals heavily rely on computer-integrated high-end technology. VR-enabled tools, such as haptic interfaces and telepresence, offer human–computer interfaces, 3D visualization, and modeling tools in the medicine industry. It can be used as surgical assistant for simulation of paranasal surgery. During a simulated operation, the system is capable of providing vocal and visual feedbacks to the user, and warns the surgeon when a dangerous action is about to take place. In addition to training, its expert assistance can be used during the actual operation to provide feedback and guidance. This is very useful when the surgeon's awareness of the situation is limited due to a complex anatomy. Telepresence techniques could allow surgeons to conduct a robotic surgery from anywhere in the world, offering increased accessibility to specialists. Advanced techniques of body analysis, such as MRI, computerized axial tomography (CAT), electroencephalogram (EEG), ultrasound, and X-rays are data-intensive activities. VR allows users to view large amount of information by navigating through 3D models. 3D modeling tools can be used to develop artificial organs and models of the various body parts. VR can also be used for motion analysis, rehabilitation and physical therapy. Motion analysis can help train athletes to prevent injuries and improve performance. Medical professionals can use VR to study a body by navigating in and around it. For example, a 3D model of leg motion could be used to observe muscle dynamics while peering inside at the joints. Young surgeons could practice operations on VR cadavers; experienced surgeons could learn new techniques.

6. Robotics

Robotic systems use telepresence to help control the telerobot when performing difficult tasks. A telerobot is a robotic system controlled by a human operator at a remote control station. The remote manipulator system (RMS) of a space shuttle is such a device. An astronaut inside a space shuttle can control this arm in many tasks, such as docking with a satellite and removing payload. Virbots is an example of virtual robots used for artificial intelligence and virtual computer applications. Virtually-enabled telerobotics are used to allow people to perform activities in dangerous worlds such as outer space, areas with chemical or living hazards, battlefields, oilfields, and under the sea. Virtually-enabled automation is also used for macro-scale activities (such as mineral extraction, landscaping, and architecture) and tiny-scale activities (such as surgery on a micro-scale, genetic engineering, and virtual biology). Robots (whether teleoperated, under supervisory control, or autonomous) have been used in a variety of applications in maintenance and repair. Nuclear industry and highways are important areas where maintenance and repair is well conceived by these virtually-enabled robots. Robotic solutions to highway maintenance applications are attractive due to their potential for increasing the safety of the highway workers, reducing delays in traffic flow, increasing productivity, reducing labor costs, and increasing quality of the repairs. Railways are another area which has lead to the development of a number of robotic solutions to maintenance and repair applications in the industry. Powerline maintenance and aircraft servicing are other promising area where maintenance robots have shown their remarkable presence.

7. Military

One of the first areas where VR finds practical application is military training and operations. The views of military applications of applying VR can be a simulation of reality, as an extension of human senses through telepresence or as an information enhancer through augmented reality. Smart weapons and remotely-piloted vehicles (RPVs) were developed, because many aspects of combat operations are very hazardous and more risky if the combatant seeks to improve his performance. VR allows the shooter and weapon controller to launch the weapon and immediately seek cover and exploring safe place. It could be used for information enhancement in a military operation in adverse conditions and night times. The objective is to supply the pilot or tank commander with much of the necessary information. The air force uses the HUD that optically combined critical information such as altitude, airspeed, and heading details with an unobstructed view through the forward windscreen of a fighter aircraft. This combination of real and virtual views of the outside world can be extended to nighttime operations. Using an infrared camera mounted in the nose of the aircraft, an enhanced view of the terrain ahead of the aircraft can be projected on the HUD.

8. Other applications

VR technology has potential to contribute to every aspect of our daily activities. Beside the above mentioned application areas, few other noticeable areas where VR can contribute include the following.

Business

VR offers many improvements and inexpensive alternatives to present systems that are being used in the industry. Some of the areas in which VR is showing its impact are spreadsheets, the stock market, information management, virtual designs, and virtual prototyping. Businesses can customize the way it represents and communicates real and abstract data in order to allow employees to utilize their human talent to their maximum potential.

Tool for handicapped

VR's input devices offer new ways of communicating and navigating. The wired glove is a part of a system called Glove Talker that relates specific glove movements to specific sounds. So, the computer can speak for persons who have lost the ability to speak. Quadriplegics have used VR technology to move objects on a computer screen using only their eyes. Biosensors can be used to control robotic manipulation.

Sports and fitness

Proper physical training and sports activity in the absence of an expert physical or trainer is compensated by VR tools. VR offers the potential to enhance sports and fitness by creating realistic simulations and enhancing the experience of indoor and outdoor exercises.

Object modeling and computer architecture for Virtual Reality

Introduction

Virtual world requires more detail representation of object. Natural physical attributes are added together with geometric descriptions to achieve realism. The behavioral aspects including interaction among multiple objects and effect of physical aspects of the world is also important. Object modeling in virtual reality applications must consider all these issues for designing and developing VR applications.

Modeling Techniques

In order to model the objects algorithms must be implemented on computer systems. Here traditional mathematical methods do not fit well. While traditional mathematics rely on continuous functions, computer systems require discrete definitions. 3D modeling is the process of developing a mathematical, wireframe representation of any 3D object (either inanimate or living) via specialized software. The product is called a 3D model. It can be displayed as a 2D image through a process called 3D rendering or used in a computer simulation of physical phenomena. 3D models represent a 3D object, using a collection of points in 3D space, connected by various geometric entities such as triangles, lines, and curved surfaces.

Different types of modeling include:

- Geometric modeling
- Kinematics modeling
- Physical modeling
- Behavioral modeling

Geometric modeling

Geometric modeling describes the shapes of virtual objects such as polygons, triangles, vertices, and splines. Moreover, it also specifies their appearances such as surface texture, surface illumination, and color. The shapes of the virtual objects are defined by their 3D surface that again can be determined in many ways. The most common way to describe the surface of a virtual object is by using a triangular mesh, as they use shared vertices and happens to be faster in rendering. Though used widely in simple surface descriptions, these are not preferred for representing objects with highly curved and bumpy surfaces. In such cases, the alternative is to use parametric surfaces as described in the book. Parametric surfaces come to disadvantage when they undergo deformation. Several methods to construct the object surface include the use of a toolkit editor, importing CAD files, using a 3D digitizer, 3D scanning, and models from existing databases.

The first step in generating the realistic look of 3D is modeling the geometry of a virtual object. The second step is illuminating it so that objects in the scene become real and visible. The appearance of the objects in the scene depends on the placement of light sources, their types, shading models, and the surface properties determining the reflectivity coefficient. Surface texture is another important factor in realism of good 3D virtual objects.

Kinematic modeling

Kinematics deals with the study of describing and modeling how objects move. Kinematic equations can be used to determine information about an object's motion. Kinematic modeling is an important step in modeling virtual world after defining the object shape and their appearance. It specifies the spatial description of the virtual objects in the world coordinate system, as well as their relative position in virtual world.

Factors that affect the kinematic modeling include

- Motion of a virtual camera
- Visual feedback by transforming images to project them on a 2D display
- Maintaining parent – child hierarchical relationships that shows the effect of movement of the parent object to the child in the virtual scene.

Object hierarchies define groups of objects that move together as a whole, but whose parts can also move independently. Use of homogeneous transformation matrices facilitates kinematic operations including translation, orientation, clipping, and relative viewing of the virtual objects. Mapping the virtual objects to the camera coordinates is the first stage of rendering pipeline. It is followed by illumination, perspective views and projection, clipping, and screen mapping. Screen mapping translates and scales the (x, y) vertex coordinates of the virtual objects inside the viewing cube or frustum to the dimensions of a 2D display window.

Physical modeling

Physical modeling is the next important step after geometry and kinematics in modeling a virtual world. Physical modeling is concerned with integrating the objects' physical characteristics for bringing realism to the virtual world. It includes bringing the contribution of an object: weight, inertia, surface roughness, and deformation modes, including elastic and plastic properties. Hence any physical modeling process must consider the role and contribution of collision detection, calculation, mapping, and smoothing of force, and haptic texturing. Collision detection is the first stage in physical modeling that determines whether two or more objects are in contact with each other.

The next aspect in physical modeling is force computation, wherein it takes account of the type of surface contact, the kind of surface deformation and the object's physical and kinematic characteristics. The user is expected to feel the reaction forces. The force computation can be planned in accordance to the type of object being haptically simulated.

Haptic texturing enhances the realism of the physical model of the virtual object surface by adding new information to characterize the object as smooth, slippery, cold, etc. Haptic texturing can be used to create new surface effects such as multi-texturing. Applying additional forces to the haptic interaction device, when in contact with the surface, it is possible to simulate surface texture and friction.

Behavior modeling

Object appearance, kinematics, and physical property simulations are based on mathematical modeling. Whenever objects interacted, it was controlled by the user. Another approach is to model the object behavior independent of the user's action. It is specifically suited for large and complex simulation environments, where it is not possible to control all the interaction that take place. For example, the dynamic behavioral modeling of the driving and environmental conditions related to vehicle dynamics and high fidelity math models correctly simulate operations of a vehicle with full collision detection in a 3D environment. The simulation responds to instructor-controlled parameters, representing a range of weather conditions like rain, fog, day, and night effects. Limitations and obstructions caused on the driving route by moving and stationary traffic, people movement, and truck and animal movement can also be incorporated using behavioral modeling. Behavioral modeling makes use of interactive objects, virtual agents, and crowds. Virtual agents are usually 3D character that has human behavior. Groups of such agents are called crowds and said to have crowd behavior.

The behavioral model includes emotions, behavioral rules and actions. Emotion-based behavior filters perceptual data through likes, dislikes, anger, or fear. Two agents, interpreting the same sensorial data, can take different actions in the simulation environment.

Another behavioral model includes reflex model that could tackle its opponent every time it encounters. The reflex behavioral model makes use of agents that recognize and mimic the user's actions. Groups of agents form crowds whose autonomy does not have to match that of its agents. Crowd behavior simulations have been used to study responses and reaction for public threats and attacks. It has been successively implemented in building-evacuation simulations, where the crowd behavior is in response to a common threat.

Model management

It is evident that a highly populated virtual world results in a very complex model, which is difficult for the VR engine to handle at real time. The space and time complexity of such models are extremely large, affecting the consistency in visual display and data access from secondary disks. Hence rendering of a highly complex VE with large number of virtual objects becomes almost impossible at high rates. Model management is the answer to the problem. Model management helps the VR engine in rendering a complex VE at predefined interactive rates without affecting the simulation quality.

Different approaches of model management include

- Level of detail
- Cell segmentation
- Pre-computations
- Database management

One or more of these may be required for efficient and interactive rates of display.

Level-of-detail (LOD) management

LOD deals with selecting the appropriate object level of detail for improving the rendering in graphics pipeline. Two classes of LOD management used in the VR literature are:

- Static LOD management – based on the parameters such as discrete object geometry, blending, and morphing
- Adaptive LOD management - results in much smoother simulation.

Cell segmentation

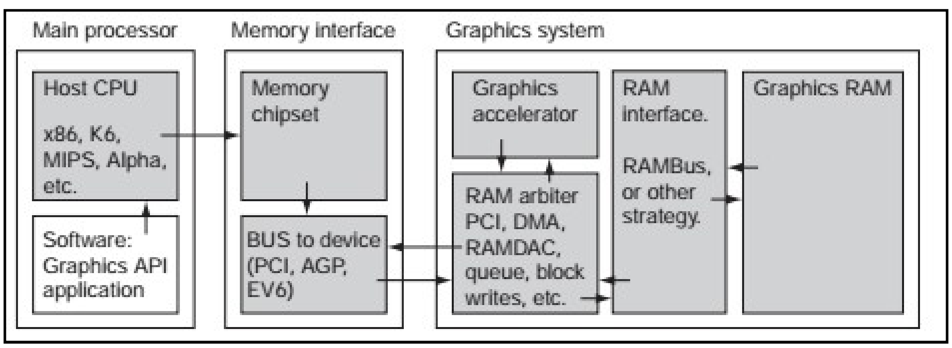
Cell segmentation solves the problem of memory access of data from hard drive in the case of larger models. The matter of attention for larger models is that they have severe impact on memory swaps for rendering needs. To minimize the simulation frame rates partitioning the large models into smaller ones has emerged as a solution. Each of which in turn can be rendered independently using static or adaptive LOD management. A form of cell segmentation called automatic cell segmentation addresses the issue by portioning the virtual world in to smaller cells, wherein only the objects within the current cell will be rendered. This reduces the complexity of rendering by a significant amount. It can be used in applications such as architectural modeling of large building and spatial GIS maps.

Another approach solving the issue of very large models involves combined cell, LOD and database method to achieve the rendering objectives. Combined cell segments subdivide the model into groups of combined cell, and database management pre-fetches the portion of the model depending upon the view area. LOD is used on fetched cells to prioritize the order in which models are loaded in the rendering pipeline. Hence the limited computational power available, and the desire for simulation realism demands management of model size and complexity, level of detail, and cell segmentation.

PC graphics architecture and accelerators

As personal computers (PC) form the base of a large computing environment today, millions of units are in use today. Real-time graphics rendering involves drawing a desktop graphical user interface (GUI), playing a game or real-time simulation or an animation.

The block diagram explaining modern graphics architecture is shown in Figure.



Graphics accelerators generally refer to coprocessors that reside in the computer that assist in drawing graphics. Also known as a 3D accelerator, the graphics accelerator card is generally an internal board that is installed into the peripheral component interconnect (PCI) or accelerated graphics port (AGP) slot and reduces the time it takes to produce images on the computer screen by incorporating its own processor and memory. Graphics accelerators speed up the display of images on the monitor, making it possible to achieve effects not otherwise possible—for example, the presentation of very large images or of interactive games in which images need to change quickly in response to user input. Many new PCs are now sold with a graphics accelerator built in.

The power of a graphics accelerator can be extended further if the PC is equipped with the AGP, a bus (data path) interface between the computer components involved in image display. Each graphics accelerator provides an application program interface

(API). Some support more than one API. Among the most popular APIs are the industry standard OpenGL and Microsoft's DirectX and Direct3D.

GUIs such as Windows take advantage of these if a "display driver" is available to perform graphics more efficiently than purely software-based algorithms. More recently purchased computer systems are more likely to have a built-in graphics accelerator.

A graphics accelerator assists graphics rendering by supplying primitives that it can execute concurrently with and more efficiently than the earlier ×86 CPU.

The main reason a graphics accelerator improves overall graphics performance is because it executes concurrently with the CPU. This means that while the CPU is calculating the coordinates for the next set of graphics commands to issue, the graphics accelerator can be busy filling in the polygons for the current set of graphics commands. This dividing up of computation is often referred as load balancing.

The superiority of modern graphics accelerator is measured by screen resolution and refresh-rate capabilities, TV-out compatibility, video playback, image quality, and 2D GUI primitive support. 2D-only cards are no longer being taken seriously since the driving force of recent times is their 3D capabilities. When taking into account different architectures for graphics accelerators, few factors that must be accounted include: cost of development, performance, compatibility, and features.

Performance bottlenecks

The most encountered bottlenecks for applications that wish to maximize graphics performance include

- Graphics memory bandwidth
- Communication between host and graphics accelerator
- Host feature emulation
- Monitor refresh problems

The memory upload performance from host to graphics memory that was a serious bottleneck has been solved to some extent by AGP (Accelerated Graphics Port) technology. The biggest bottleneck in graphics performance is the speed at which the accelerator can output its results to memory. Accelerator companies such as ATI experimented with video random access memory (VRAM), a kind of RAM technology that could allow multiple accesses per cycle (one for video refresh and one for accelerator output) for improving performance.