

Introduction to Virtual Reality & 3D User Interfaces

029515
2010년 봄학기
3/15/2010
박경신

3D User Interfaces

What are 3D User Interfaces?

- ❑ Interaction techniques (e.g. drag-and-drop), interface widgets (e.g. pull-down menus), interface metaphor (e.g. desktop metaphor) for 2D desktop computer
- ❑ A new set of interface components, such as new devices, new techniques, new metaphors, needed for nontraditional computing environments/applications, e.g. wearable-computers, HMD, VR, mobile device, etc
- ❑ 3D User Interface (3DUI) is a way for the user to communicate with a 3D application using 3D input and 3D interaction techniques
- ❑ 3DUI allows us to provide both immersion and interactivity

Why 3D User Interfaces?

- ❑ 3D interaction is relevant to real-world tasks
- ❑ The technology behind 3DUIs is becoming mature
- ❑ 3D interaction is difficult
- ❑ Current 3DUIs either are simple or lack suability
- ❑ 3DUI design is an area ripe for future work

Virtual Reality

What is Virtual Reality?

- ▣ Possible definition:
 - Immersion into an alternate reality or point of view, e.g. book, movie
- ▣ Popular conception of VR
 - Star Trek: The Next Generation Holodeck
 - The Matrix
- ▣ A better definition of VRMedium composed of interactive computer simulations that sense the participant's position and replace or augment the feedback to one or more senses



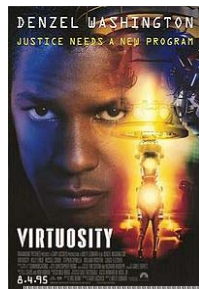
What is Virtual Reality?

Virtual Reality

- ▣ Virtual reality (VR) is a technology which allows a user to interact with a computer-simulated environment, but it a real or imaged one. Most current virtual reality environments are primarily visual experiences, displayed either on a computer screen or through special stereoscopic displays, but some simulations include additional sensory information, such as sound through speakers or headphones. Some advanced, haptic systems now include tactile information, generally known as force feedback, in medical and gaming applications.
 - wikipedia



Lawnmower Man (1992) Virtuosity (1995)



The Matrix (1999)



Avatar (2009)



Disclosure (1994)



Johnny Mnemonic (1995)

Virtual Reality

- 가상현실 (Virtual reality; VR) 은 3차원의 공간성, 실시간의 상호작용성, 자기 투사성의 세 요소를 수반한다. 인터페이스는 일반적으로 시각과 청각을 이용하지만, 촉각, 힘의 감각, 전정 감각 등, 다양한 인터페이스(멀티모달 인터페이스)를 이용한다. 1968년에 유타 대학의 Ivan Edward Sutherland에 의해서 HMD (Head Mounted Display, 머리 부분 탑재형 디스플레이)가 제안된 것이 최초의 가상현실이다. 시각을 이용한 가상현실로서는, 1991년에 일리노이 대학의 Thomas DeFanti 등에 의해서 제안된 CAVE (Cave Automatic Virtual Environment, 몰입형의 투영 디스플레이)가 유명하다. – 한국 위키백과

Characteristics of VR

Characteristics of VR

- Computer generated 3D world & real-time graphics
- Immersion (i.e., viewer-centered perspective)
- Interactivity (i.e., user controls)
- Sensory feedback (e.g. visual, audio, haptic feedback)

Virtual World

- The **contents** conveyed by a medium
- An imaginary space often manifested through a medium
- A description of a **collection of objects** in a space, and the **rules** and **relationships** governing those objects

Immersion

- ▣ Also called **presence** (being mentally immersed)
- ▣ **Sense of "Being there"** perspective
- ▣ To enhance immersion:
 - First-person view
 - Wide field-of-view
 - Stereo vision
 - Head tracking
 - Auditory, haptic or tactile feedback

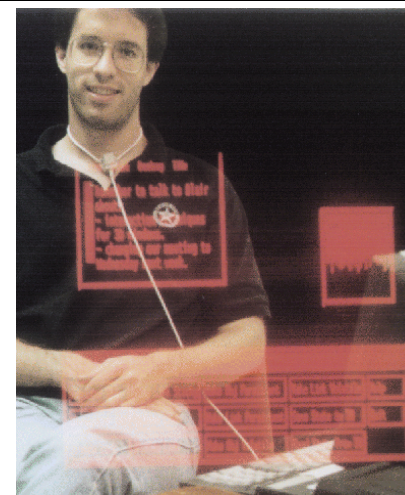
Interactivity

- ▣ The viewer controls interactively in the environment
- ▣ **Tracking** is the key to **interactivity**. The movement of the participant is being tracked and monitored as to yaw, pitch, roll and the position in x, y, z.
- ▣ The participants **interact with objects, characters, places in a virtual world** – i.e., manipulation and navigation.
- ▣ Collaborative environment refers to multiple users interacting within the shared virtual space or simulation. The user are represented as their avatars.

Sensory Feedback

- ▣ VR provides **direct sensory feedback** to the participants
- ▣ Mainly rely on visual sense
- ▣ Immediate interactive feedback requires the use of a high-performance computer
- ▣ To provide sensory output of the VR system on the position of the participants, the system must track their movement.

Other forms of VR

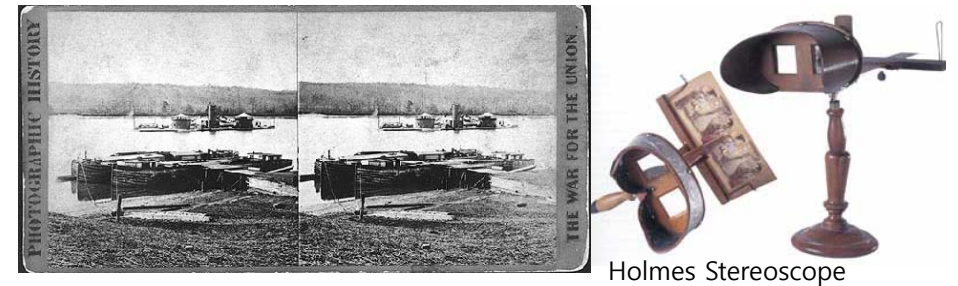


- ▣ Artificial Reality
- ▣ Virtual Environment
- ▣ Cyberspace
- ▣ Augmented Reality
- ▣ Tele-presence
 - Controlling a probe in a deep ocean area
 - Working with dangerous chemicals

VR History

VR History

- ❑ 1838 – Stereoscope, by Charles Wheatstone
- ❑ 1849 – Lenticular Stereoscope, by Brewster
- ❑ 1903 – Parallax Barrier, by Ives
- ❑ 1908 – Integral Photography, by Lippmann
- ❑ 1948 – Holography, by Gabor



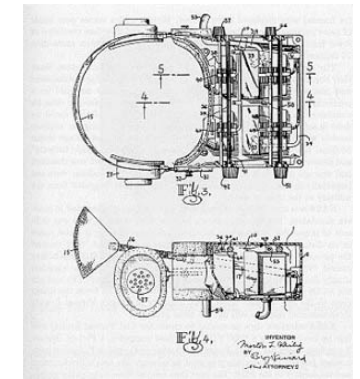
VR History

- ❑ 1956 - Morton Heilig's **Sensorama**
 - Cinematographer
 - Wanted to expand on 'cinerama' which had 90 degree field of view (FOV) by shooting with 3 cameras simultaneously and then synchronized when projected. Academy ratio films typically had 18 degree FOV, and Cinemascope 55 degree (depending on where you sat in the theatre)
 - Designed and patented '**the experience theatre**' - 180 degree horizontal and 155 degree vertical. 30 speakers, smell, wind, seats that moved.
 - Couldn't get funding so he made the scaled down '**sensorama**' - arcade setup with a vibrating motorcycle seat and handlebars and 2 35mm projectors for stereo and wind and aromas and stereo sound as viewer moved through prerecorded experiences – **for multi-sensory virtual experience**
 - Patented first head mounted display (1960) - used slides - couldn't get funding.

Sensorama



Heilig's Sensorama

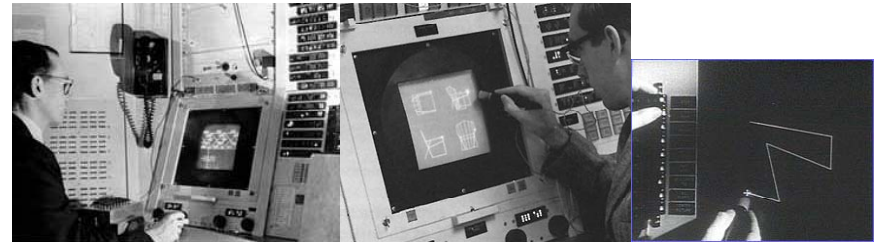


Heilig's US patent for HMD

VR History

- ❑ 1963 - Ivan Sutherland @ MIT
 - **Sketchpad**, interactive computer graphics
- ❑ 1965 - Ivan Sutherland @ University of Utah
 - Proposes the '**ultimate display**' which is basically Star Trek's holodeck complete with the computer controlled generation of matter. "The ultimate display would, of course, be a room within which the computer can control the existence of matter. ... With appropriate programming such a display could literally be the Wonderland into which Alice walked"
- ❑ 1966 - Ivan Sutherland
 - Created '**Sword of Damocles**' - first HMD
 - Real-time computer generated display of wireframe cube with head tracking projected onto half-silvered mirrors so the cube floats in front of the user in the room (what we would call augmented reality today.) Two CRTs mounted by the users head along with other hardware suspended from the ceiling by a mechanical arm.

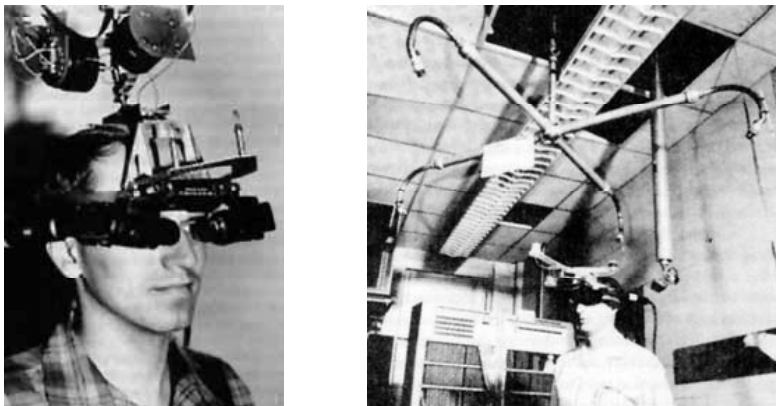
Sketchpad



Ivan Sutherland's Ph.D dissertation at MIT,
[The Sketchpad: A Man-Machine Graphical Communication System \(1963\)](#)

The first interactive computer graphics system with a light-pen for design and engineering.

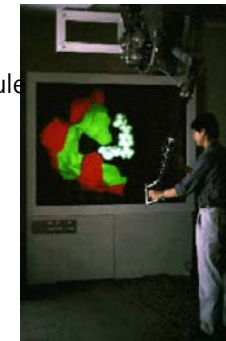
Ultimate Display



Sutherland's "Ultimate Display"

VR History

- ❑ 1967 - GROPE @ UNC
 - Force-feedback project (began in 1967)
 - GROPE-I – 2D system for continuous force feedback
 - GROUP-II – 6DOF (with 3 forces and 3 torques)
 - GROUP-III – a full 6-DOF molecular docking system
 - UNC uses a ceiling mounted [ARM \(Argonne Remote Manipulator\)](#) to test receptor sites for a drug molecule



UNC's GROPE II 6-DOF ceiling mounted ARM
(Argonne Remote Manipulator)

VR History

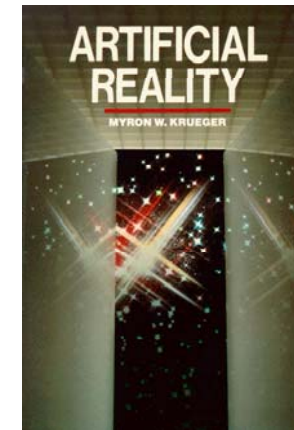
- 1970 - Myron Krueger
 - VIDEOPLACE - 'artificial reality' where cameras are used to place people into projected scenes
 - Image processing used to track the users in the 2D space



Krueger's Videoplace

Artificial Reality

- 1983 - Myron Krueger published his famous book, *Artificial Reality*.



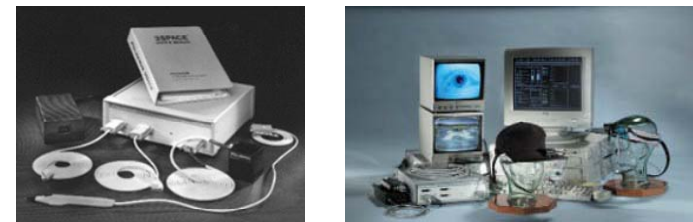
VR History

- 1977 - Sayre, DeFanti, Sandin @ EVL
 - The Sayre Glove** - the inexpensive, lightweight, first data glove for gesture recognition
 - This glove uses light-conductive tubes to transmit varying amounts of light proportional to the amount of finger bending.
- 1978 - Andrew Lippman, Michael Naimark, Scott Fisher @ MIT
 - The Aspen Movie Map**
 - The first true hypermedia system
 - It was a surrogate travel application that allowed the user to enjoy a simulated ride through the city of Aspen, Colorado



VR History

- 1979 - F.H.Raab, et al. utilized tracking systems in VR - the **Polhemus** (6-DOF electromagnetic position tracking)
 - Bill Polhemus started Polhemus Associates in 1964, working on projects related to navigation for US Dept of Transportation



Polhemus FASTrak and VISIONTrak tracking system

VR History

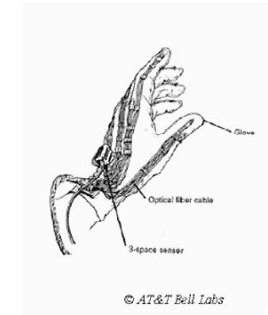
- 1982 – Thomas Furness III
 - VCASS (Visually Coupled Airborne Systems Simulator)
 - 6 degree of freedom HMD which isolated user from the real world
- 1986 – Thomas Furness III
 - Virtual Super Cockpit for pilots that fed 3D sensory information directly to the pilot, who could then fly by nodding and pointing his way through a simulated landscape below.
- 1989 – Thomas Furness III
 - found HITlab (Human Interface Technology Laboratory)



*Super Cockpit Program
Wright Patterson AFB
1986-1989*

VR History

- 1983 – Grimes' Digital Data Entry Glove @ Bell Labs
 - The first widely recognized device for measuring hand position.
 - Finger flex sensors, tactile sensors at the fingertips, orientation sensing and wrist-positioning sensors.



© AT&T Bell Labs

VR History

- 1984 - Michael McGreevy, et al.
 - VIVED (Virtual Visual Environment Display) created inexpensive HMD with off-the-shelf components (e.g. Sony watchman, DEC PDP 11, Picture System2 graphics computer, and a Polhemus noncontact tracker)
 - Scott Fisher @ NASA Ames continues to add features: data glove, quad-sound, voice control, etc becoming VIEW (Virtual Interface Environment Workstation)

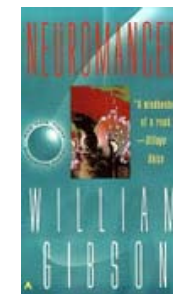


By 1988, four 3D virtual sound sources were added.

VIVED evolved into VIEW (Virtual Interface Environment Workstation)

VR History

- 1984 – William Gibson
 - In **Neuromancer**, he added the word "**cyberspace**" – the implications of a wired, digital culture, and have had tremendous influence on the scientists, researchers, theorists, and artists working with virtual reality.
 - Cyborgian, cyber-habitats, virtual communities, online chat spaces



VR History

- 1985 - Jaron Lanier, Thomas Zimmerman & VPL Research
 - **Term: Virtual Reality**
 - First company focused on VR products
 - Sold **VPL data gloves** in 1985 and eye phones in 1988



VPL Data Glove



VIEW system, NASA Ames Research Center

VR History

- 1986 – Ascension Technologies founded from former Polhemus employees, Ernie Blood and Jack Scully
 - Develop a wide range of electromagnetic tracking systems for various applications, such as animation, medical imaging, biomechanics, virtual reality, simulation, military



Ascension Flock of Birds motion tracker



Puma helicopter repair training system

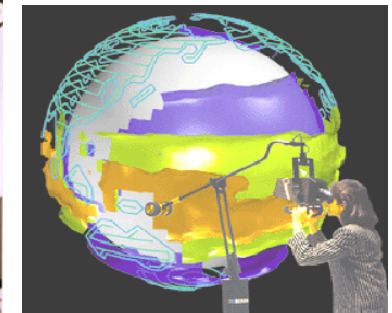
VR History

- 1987 – **Virtual Cockpit** (British Aerospace)
 - Head and hand tracking, eye tracking, 3D visuals, 3D audio, speech recognition, vibro tactile feedback
- 1989 - Autodesk
 - First PC based VR system
- 1989 - Fakespace Lab
 - Development of the **BOOM (Binocular Omni-Orientation Monitor)**



Virtual Cockpit

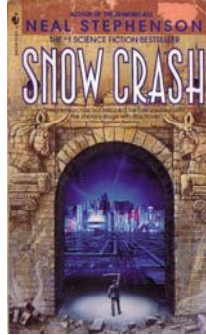
BOOM



BOOM commercialized by Fakespace

VR History

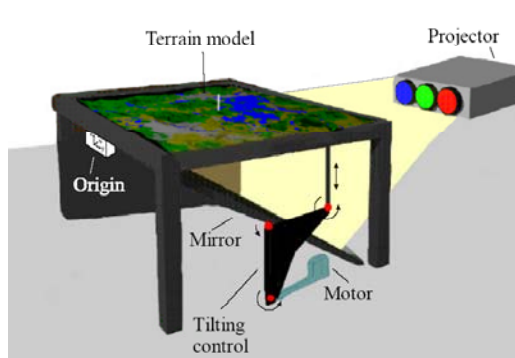
- ❑ 1992 – Snow Crash
 - Neal Stephenson's best selling science fiction novel, published in 1992. **Snow Crash**, details a highly compelling conception of the "**Metaverse**" – a networked hyper-realistic virtual universe. The term "**avatar**" was extensively referred to describe one's representation in a virtual world.



VR History

- ❑ 1991 – ICAT (International Conference on Artificial Reality and Telexistence)
- ❑ 1992 – Development of the [CAVE](#) @EVL
- ❑ 1993 – Silicon Graphics Reality Engine
 - Hardware-supported Gouraud shading, texture mapping, z-buffering, anti-aliasing
- ❑ 1993 – OpenGL standard
- ❑ 1993 – Development of the [Immersive Workbench](#),
 - by GMD (German National Research Center for Information Tech)
- ❑ 1993 – Development of [PHANTOM](#) by SensAble Technology
- ❑ 1993 – Development of [Virtual Retinal Display](#) by HIT lab
- ❑ 1995 – IEEE Virtual Reality Annual International Symposium

Immersive Workbench



Immersive Workbench



Phantom



Phantom Desktop

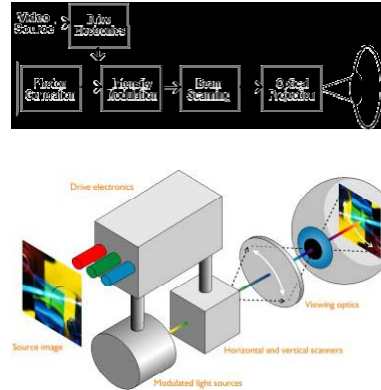


Phantom Omni

Virtual Retinal Display



Figure 3: Virtual retinal display technology is being incorporated in helmet-mounted displays for military applications. (Photo courtesy of Mikrovision).



VR History

- ❑ 1995 – Development of the **ImmersaDesk** @ EVL
- ❑ 1996 – **Intersense** founded
 - Create a wide range of ultrasonic/inertial motion trackers
- ❑ 1998
 - Disney opens the first of their **DisneyQuest** family arcade centers, which features numerous VR attractions using both HMD and projection-based visual displays
 - The first six-sided CAVE installed at the Swedish Royal Institute of Technology
- ❑ 2000 – Development of **Geowall** @ EVL
- ❑ 2002 – PC graphics & PC clusters
- ❑ 2003 – University of Arizona
 - Development of SCAPE and the Head Mounted Projective Display
- ❑ 2003 – Development of **PARIS** and **Varrier** @ EVL
- ❑ 2003 – **Second Life** @ Linden Lab
- ❑ 2005 – **SONY's patent** on Brain Computer Interface

CAVE



ImmersaDesk



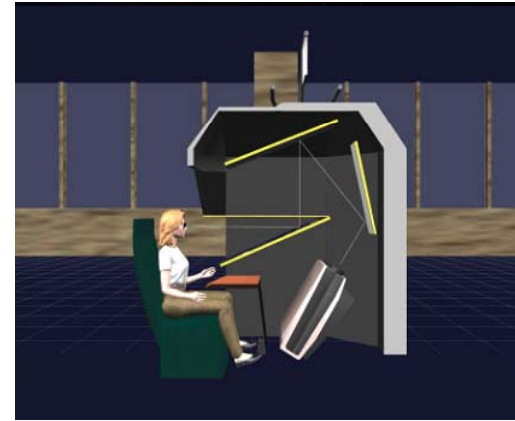
- ❑ 1992 – 1 CAVE
- ❑ 2001 – at least 50 CAVEs & at least 100 ImmersaDesks around the world
- ❑ Now available from Silicon Graphics Inc. and FakeSpace Systems Inc.

GeoWall



- Originally designed & developed by EVL in 2001
- Now widespread adoption by GeoWall Consortium for research & education in the Geosciences (at least 70 GeoWall)
- www.geowall.org

PARIS



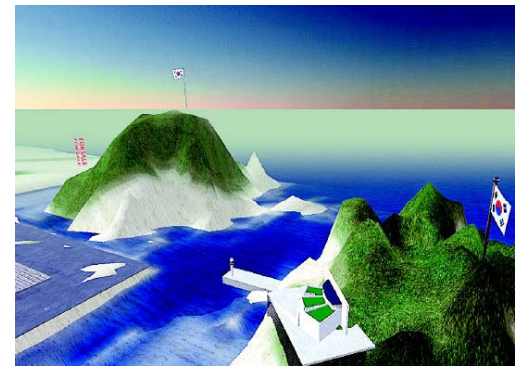
- PARIS (Projected Augmented Reality Immersive System))
- Projection-based "augmented" virtual reality system
- Half-silver mirror superimposes the displayed image over user's hands

Varrier



- Varrier Tiled Auto-Stereoscopic LCD Display
- Use barrier strip material in front of LCD to create autostereoscopic image.
- 4 horizontal pixels to create 1 stereoscopic pixel- oversampling to reduce aliasing.
- Use low-latency tracking to eliminate pseudo-stereo.

Second Life



- Launched on June 23, 2003 by Linden Lab
- 3D virtual world that enables its users to interact with each other through avatars
- <http://www.serakorea.com/>

SONY's Patent on Brain Computer Interface

2005 – Sony takes 3-D cinema directly to the brain

From *The Times*
April 7, 2005

Sony takes 3-D cinema directly to the brain

By Michael Horsnell

✓ RECOMMEND? (1)

THE cult sci-fi movie *The Matrix* might not have such an improbable plot after all.

The first step towards a real-life version, in which cyber-reality is projected into the brains of people via an electrode feed, could be just over the horizon.

Sony, the Japanese entertainment giant, has patented an idea for transmitting data directly into the brain, with the goal of enabling a person to see films and play video games in which they smell, taste and perhaps even feel things, *New Scientist* magazine says.

The patent is based purely on theory, not on any invention — but they used to say that man would never fly.

In Sony's patent, the technique would be entirely noninvasive. It would not use brain implants or other surgery. The patent has few details, describing only a device that would fire pulses of ultrasound at the head to modify the firing patterns of neurons in targeted parts of the brain.

The aim, it says, is to create "sensory experiences", ranging from moving images to tastes and sounds.

EXPLORE UK NEWS

- CRIME NEWS
- EDUCATION NEWS
- HEALTH NEWS
- SCOTLAND NEWS

TIMES RECOMMENDS

- How a gift horse revived island race
- The collective art of doing it on the cheap
- Helena Bonham Carter: 'I'm not a dirty person'

HUMAN FACE OF GANGS



An alternative view of London's mean streets

The Movie Avatar

2009 – AVATAR

- Avatar is a 2009 American science fiction epic film written and directed by James Cameron. The film's title refers to the genetically engineered Na'vi and human hybrid bodies used by several human characters to interact with the natives of Pandora.



Avatar: James Cameron and Peter Jackson (left) make final preparations for an epic battle that will decide the fate of an entire world. Photo credit: WETA.

TM and ©2009 Twentieth Century Fox Film Corporation. All rights reserved. Not for sale or duplication.

VR Applications

Current Uses of VR

- Vehicle Design and Architectural Walkthroughs
- Education and Training
- Therapy and Rehabilitation
- Scientific Visualization
- Cultural Heritage
- Art and Entertainment

Vehicle Design & Manufacturing



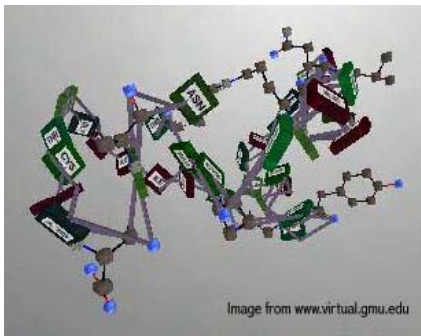
- Visual Eyes developed by General Motors Research, Hughes Research Lab & EVL
- Rapid prototypes for reviewing computer generated 3D CAD models

Architectural Walkthroughs



- Architectural Linked Immersive Environment (ALIVE) by SARA, The Netherlands & EVL
- Dutch architect Rem Koolhaas' design of the new Campus Center at the Illinois Institute of Technology in Chicago
- ALIVE lets viewers navigate through 3D CAD models

Education



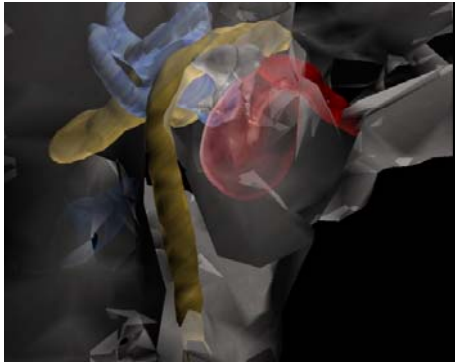
- Science Space for high school or college students, using HMD by George Mason University & University of Houston
- Newton World allows students to experience Newton's three laws where they control the environment
- Maxell World examines Gauss's Law by examining the nature of electrostatic forces and fields
- Pauling World studies chemical structure of molecules

Education



- For elementary students, by EVL
- NICE (Narrative Immersive Constructionist Environments) Persistent garden
- Round Earth Project is intended to teach young children the concept of a spherical Earth
- Virtual Ambients is designed to help students improve early stages of students' scientific inquiry skills

Medical Training



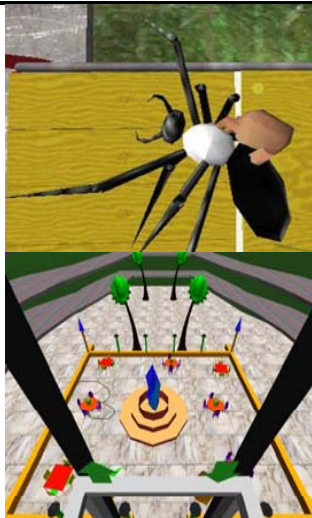
- Virtual Temporal Bone, developed by UIC's VR Medicine Lab lets physician teach medical students about 3D structure and function of the inner ear
- External view of the human ear
- Human temporal bone to reveal the delicate anatomic structures imbedded within bone
- Closeup view of the structure within the bone

Military Training



- NPSNET – Large Scale Virtual Environment Technology Testbed
- NPSNet is a real-time, interactive distribution simulation system, developed by Naval Postgraduate School

VR Therapy



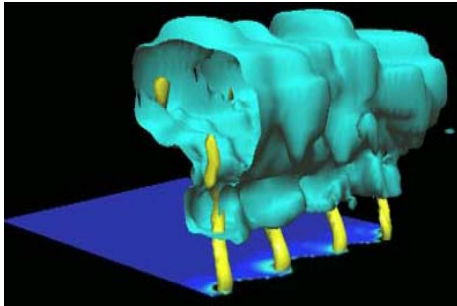
- Spider phobia, developed by HIT lab at University of Washington – VR exposure therapy for treating spider phobia
- Acrophobia (the fear of heights), developed by GVI at Georgia Tech – VR exposure therapy that involves exposing the subject to anxiety producing stimuli while allowing the anxiety to attenuate

VR Therapy



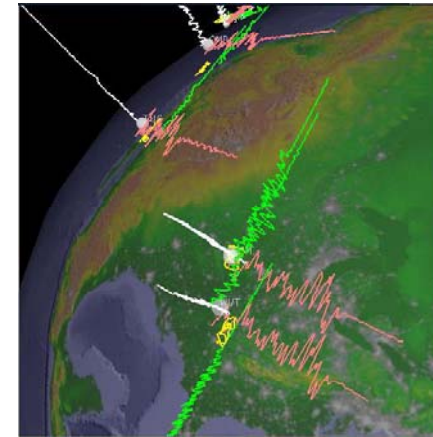
- 'Rutgers Ankle' Rehabilitation Interface, developed by Rutgers University
- Pilot the virtual plane
- The "Rutgers Ankle" Rehabilitation Interface is a robotic ankle rehabilitation device designed for at-home use and Internet-based remote monitoring by therapists

Scientific Visualization



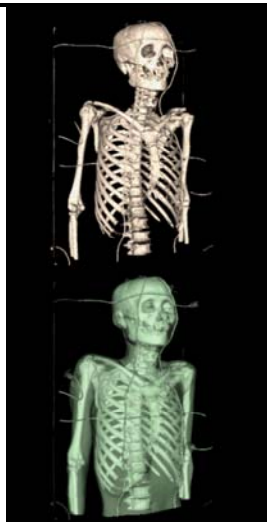
- Non-Supercell Tornado Simulation developed by UIUC Dept. of Atmospheric Sciences & NCSA
- Viewers can immerse themselves with the digital storm and understand how they form and develop

Scientific Visualization



- Wiggleview, developed by EVL
- Traditionally seismologists look at 2D X-Y plots of a time-series of the displacement of a seismometer in the North-South, East-West, and Up-Down directions
- Wiggleview allows to visualize the simultaneous recording of three channels of seismic data in response to an event

Scientific Visualization



- Visible Korean Human, developed by Computer Graphics Lab at Sogang U. & KISTI
- Volume visualization using image-based rendering technique
- CT, MRI, RGB datasets of a Korean senior, created by KISTI and Ajou Univ.
- allows users to investigate skin and bone of the human

Scientific Visualization



- Development of [Typhoon Maemi](#) landed on the southern coastal area of Korea during Sep 2003, developed by Digital Ocean & Virtual Environment Center at Korea Ocean Research and Development Institute
- Low-saline water in Yellow Sea due to spreading of Changjiang Diluted water toward Jeju Island, developed by DOVE at KORDI
- Scientific visualization to display multi-dimensional numerical data (e.g. atmospheric, oceanographic)

Cultural Heritage



- Virtual Harlem allows people at remotely located CAVEs to tour 1920-40 Harlem, and listen to African American artists, writers and intellectuals of that time - notably Langston Hughes, Marcus Garvey and others.
- Collaborative effort between Central Missouri State University, Advanced Technology Center at University of Missouri, and EVL at UIC.

Cultural Heritage



- Digital restoration of Koguryo mural painting tomb, Anak No. 3 Tumulus, in virtual reality
- Allows children and adults to experience the life and times of Koguryo people and details custom to Korea

Cultural Heritage



Interactive Art



- Crayoland created by Dave Pape, EVL – 2D crayon drawings placed in a 3D world
- Synesthesia by Rita Addison & Marcus Thiebaut, EVL – a sensory input (e.g. music) is perceived as a different sensory mode
- CAVE Quake by Paul Rajlich, NCSA

Entertainment



Disney Quest - Aladdin

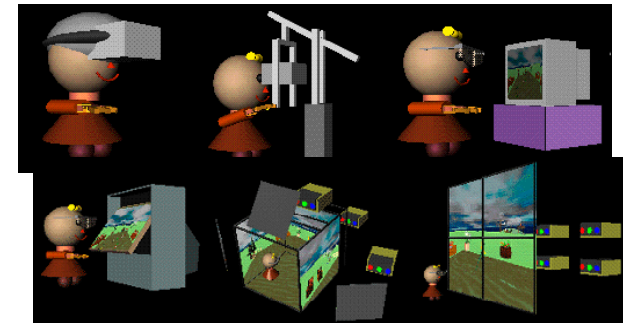
VR Components

VR Components

- ▣ Display
- ▣ Stereoscopy
- ▣ Image Generator (Computer Hardware)
- ▣ Tracking
- ▣ Input Devices
- ▣ Audio
- ▣ Networking
- ▣ Software

Display

- ▣ Head-mounted Display (including See-through VR)
- ▣ BOOM
- ▣ Fish tank VR
- ▣ Projection-based VR



Display

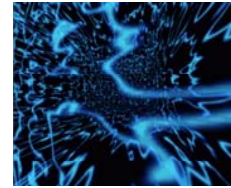
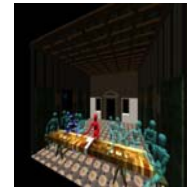
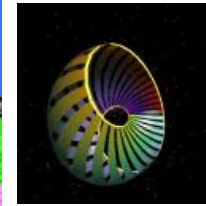


Attach display to the user



Surround the user by displays

Display



- It is important to note that although the field is called 'virtual reality', the goal is not always to create reality.
- Want to see things that can't be easily seen
- Want to create worlds that are more interesting or exotic than reality
- Want to create worlds that are simpler than real life for teaching

Display

- Computers are capable of creating very realistic images, but it takes a lot of time to render these.
- In VR we want to **at least 15 frames per second in stereo**
- For comparison:
 - Film is 24 frames per second monoscopic (with roughly 10-20 million pixels per frame)
 - Television is 30 frames per second monoscopic (with roughly 0.4 million pixels per frame)
 - HD Television is 24 or 30 frames per second monoscopic (with roughly 1 million pixels per frame)
- The tradeoff is **image quality** (especially in the area of smoothness of polygons, antialiasing, lighting effects, transparency) **vs. speed**

Stereoscopy



Stereoscopy

- ❑ If we want stereo visuals, we need a way to show a slightly different image to each eye simultaneously. The human brain then fuses these two images into a stereo image.
- ❑ One way is to isolate the users eye (As in a HMD or BOOM). Each eye watches its own independent TV.
- ❑ Another way is to use **color** – this has been done in 3D theatrical films since the 50s with red and blue glasses
- ❑ We can use **polarization** (linear or circular) – linear polarization was used in 3D theatrical films in the 80s
- ❑ We can use **time** – this was common in VR in the 90s and continues today where we show the left image then the right image and the user wears LCD shutter glasses which ensure that only the correct eye sees the correct image.

Image Generator



- ❑ Simulates virtual world, generates images and audio
- ❑ Should have fast processor, large memory, and fast graphics card
- ❑ Need a computer capable of driving the display device at a fast enough rate to maintain the illusion
- ❑ Needs two video outputs for passive stereo VR system
- ❑ Need multiple graphics engines are pretty much required if you have multiple display surfaces.

Tracking



- ❑ **6 degrees of freedom (DOF)** tracking the position (x,y,z) and orientation (yaw, pitch, roll) of the user's head, hands, or devices
- ❑ Important for immersion and interactivity
- ❑ A common tracker for low-cost systems is the Ascension SpacePad (now discontinued)
- ❑ A separate PC maybe used for tracking

Input Devices

- ❑ Input devices are perhaps the most interesting area in VR research.
- ❑ While the user can move their head 'naturally' to look around, how does the user navigate through the environment or interact with the things found there?
- ❑ Input Devices:
 - 3D mice
 - Data glove
 - Voice
 - Treadmill or bicycle locomotion system
 - Haptic
 - Tracking for gesture recognition

Input Devices



Wand



Wanda

Input Devices



Intersense IS-900 Controller



Phantom Haptic Interface

Input Device - Treadmill



Input Device - Data Gloves



cyberglove

Audio



- ▣ Ambient sounds are useful to increase the believability of a VR space (Important for Immersion)
- ▣ Sounds are useful as a feedback mechanism
- ▣ Important in collaborative applications to relay voice between the various participants
- ▣ Spatialized sound can be useful

Networking



- ▣ Often useful to network a VR world to other computers, such as supercomputers for computation and other VR devices for collaborative work
- ▣ Need high bandwidth networking for moving large amounts of data around
- ▣ Need network Quality of Service, especially latency and jitter

Software

- ▣ Most VR programming is done 'from scratch' or using lab-based software.
- ▣ 3D graphics library, such as OpenGL, Performer, Open Inventor
- ▣ VR system library, such as VRCO's CAVELib, VREC's VR Juggler, Virginia Tech DIVERSE
- ▣ VR authoring tool, such as Sense8 WorldToolkit and WorldUP, Dassault Systems 3dvia Virtools, 3Digm NOVA

Reference

- ▣ <http://www.evl.uic.edu/aej/528/lecture01.html>
- ▣ <http://www.evl.uic.edu/aej/528/lecture02.html>
- ▣ Cruz-Neira, C. (1993) Virtual Reality Overview, SIGGRAPH '93 Course Notes #23, pp. 1-18.
- ▣ A Critical History of Computer Graphics and Animation: Virtual Reality
<http://accad.osu.edu/~waynec/history/lesson17.html>
- ▣ EVL VR devices
<http://www.evl.uic.edu/research/vrdev.php3?cat=1>
- ▣ Metaverse <http://www.metaverseroadmap.org/>