PA201
Virtual Environments

Lecture 4

Virtual Reality Displays

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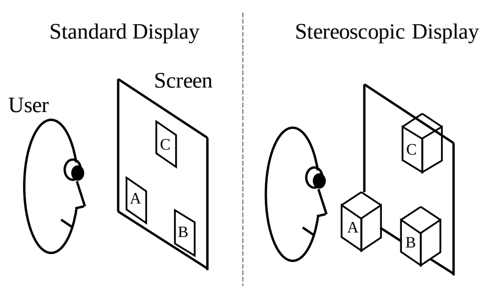
VR Immersion Levels

- Fully immersive VR applications
  - Can't experience the surrounding physical and real environment
- Semi-immersive VR applications
  - Certain degree of immersion is gained
    - i.e. Stereo projection
- Low immersion
  - 2D screen renderings of a conceptually 3D space

Standard vs. Stereoscopic Display



Light & Optics

Introduction to Light

- Knowing how light propagates in the physical world is crucial to understanding VR
- One reason is the interface between visual displays and our eyes
- Light is emitted from displays and arrives on our retinas in a way that convincingly reproduces how light arrives through normal vision in the physical world

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Introduction to Light .

- In the current generation of VR headsets, a system of both engineered and natural lenses (parts of our eyes) guide the light
- Another reason to study light propagation is the construction of virtual worlds

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Basic Behavior of Light

- Light can be described in three ways:
  - Photons: Tiny particles of energy moving through space at high speeds
    - Helpful when considering the amount of light received by a sensor or receptor
  - Waves: Ripples through space that are similar to waves propagating on the surface of water, but are 3D. The wavelength is the distance between peaks
    - Helpful when considering the spectrum of colors
  - Rays: A ray traces the motion of a single hypothetical photon. The direction is perpendicular to the wavefronts
    - Helpful when explaining lenses and defining the concept of visibility

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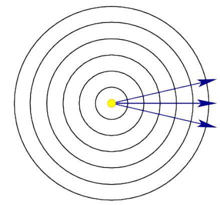
Basic Behavior of Light



Waves and visibility rays emanating from a point light source

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Lenses

- Lenses have been made for thousands of years, with the oldest known artifact
  - It was constructed before 700 BC in Assyrian Nimrud
  - Whether constructed from transparent materials or from polished surfaces that act as mirrors, lenses bend rays of light so that a focused image is formed

The earliest known artificially constructed lens

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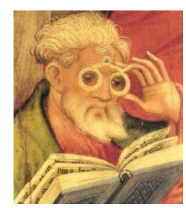
Lenses .

- Over the centuries, their uses have given rise to several well-known devices, such as eyeglasses, telescopes, magnifying glasses, binoculars, cameras, and microscopes
  - Optical engineering is therefore filled with design patterns that indicate how to optimize the designs of these well-understood devices



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Lenses ..

- VR headsets are unlike classical optical devices, leading to many new challenges that are outside of standard patterns that have existed for centuries
  - Thus, the lens design patterns for VR are still being written
  - The first step toward addressing the current challenges is to understand how simple lenses work
    - i.e. Snell's law
      - Next slide

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Snell's Law

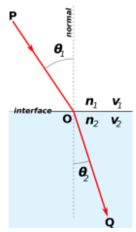
- Snell's law is a formula used to describe the relationship between the angles of incidence and refraction, when referring to light or other waves passing through a boundary between two different isotropic media, such as water, glass, or air

https://en.wikipedia.org/wiki/Snell%27s_law

Snell's Law .

- Snell's law states that the ratio of the sines of the angles of incidence and refraction is equivalent to the ratio of phase velocities in the two media, or equivalent to the reciprocal of the ratio of the indices of refraction:

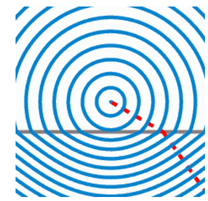
$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \frac{n_1}{n_2}$$



https://en.wikipedia.org/wiki/Snell%27s_law

Snell's Law .

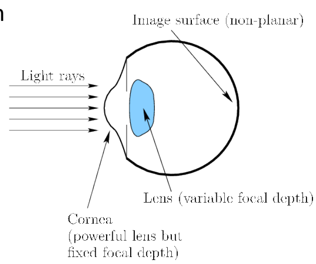
- Wavefronts from a point source in the context of Snell's law
- The region below the grey line has a higher index of refraction, and proportionally lower speed of light, than the region above it



https://en.wikipedia.org/wiki/Snell%27s_law

The Human Eye

- A simplified view of the human eye as an optical system



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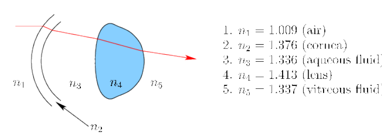
The Human Eye .

- A ray of light travels through five media before hitting the retina
- The indices of refraction are indicated
  - Considering Snell's law, the greatest bending occurs due to the transition from air to the cornea
  - Note that once the ray enters the eye, it passes through only liquid or solid materials



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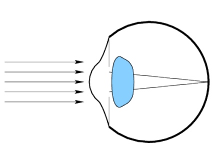
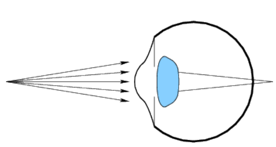
The Human Eye ..



Normal eye operation, with relaxed lens



A closer object yields diverging rays, but with a relaxed lens, the image is blurry on the retina

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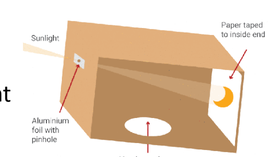
Cameras

- People have built and used cameras for hundreds of years, starting with a camera obscura that allows light to pass through a pinhole and onto a surface that contains the real image



A pinhole camera that is recommended for viewing a solar eclipse
(Figure from TimeAndDate.com)

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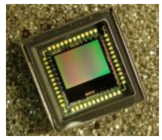
Cameras .

- 19th century
  - Various chemically based technologies were developed to etch the image automatically from the photons hitting the imaging surface
- 20th century
  - Film was in widespread use, until digital cameras avoided the etching process altogether by electronically capturing the image using a sensor
- Two popular technologies:
  - A Charge-Coupled Device (CCD) array
  - A CMOS active-pixel image sensor



A CMOS active-pixel image sensor

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Cameras ..

- Such digital technologies record the amount of light hitting each pixel location along the image, which directly produces a captured image
  - The costs of these devices has plummeted in recent years, allowing hobbyists to buy a camera module

A low-cost CMOS camera module

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Shutters

- Several practical issues arise when capturing digital images
- The image is an 2D array of pixels, each of which having red (R), green (G), and blue (B) values that typically range from 0 to 255
- Consider the total amount of light energy that hits the image plane
  - For a higher-resolution camera, there will generally be less photons per pixel because the pixels are smaller
- Each sensing element (one per color per pixel) can be imagined as a bucket that collects photons, much like drops of rain

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Shutters .

- To control the amount of photons, a shutter blocks all the light, opens for a fixed interval of time, and then closes again
- For a long interval (low shutter speed), more light is collected
  - However, moving objects in the scene will become blurry and that the sensing elements could become saturated with too much light

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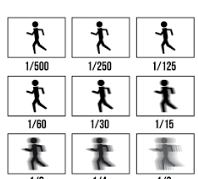
Shutter Speed

- Photographers must strike a balance when determining the shutter speed to account for the:
  - Amount of light in the scene
  - Sensitivity of the sensing elements
  - Motion of the camera and objects in the scene



Shutter Issues

- CMOS sensors unfortunately work by sending out the image information sequentially, line-by-line
- The sensor is therefore coupled with a rolling shutter, which allows light to enter for each line, just before the information is sent
- This means that the capture is not synchronized over the entire image, which leads to odd artifacts

The wings of a flying helicopter are apparently bent backwards due to the rolling shutter effect

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Shutter Issues .

- Image processing algorithms that work with rolling shutters and motion typically transform the image to correct for this problem
- CCD sensors grab and send the entire image at once, resulting in a global shutter
- CCDs have historically been more expensive than CMOS sensors, which resulted in widespread appearance of rolling shutter cameras in smartphones
  - However, the cost of global shutter cameras is rapidly decreasing

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Aperture

- The optical system also impacts the amount of light that arrives to the sensor
- Using a pinhole light would fall onto the image sensor
  - But it would not be bright enough for most purposes
    - Other than viewing a solar eclipse
- Therefore, a convex lens is used instead so that multiple rays are converged to the same point in the image plane
  - This generates more photons per sensing element

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Aperture .

- The main drawback is that the lens sharply focuses objects at a single depth, while blurring others
- In the pinhole case, all depths are essentially **in focus**, but there might not be enough light
- Photographers therefore want to tune the optical system to behave more like a pinhole or more like a full lens, depending on the desired outcome

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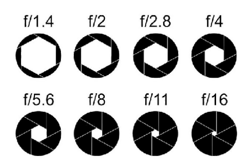
Aperture ..

- The result is a controllable aperture which appears behind the lens and sets the size of the hole through which the light rays enter
  - A small radius mimics a pinhole by blocking all but the center of the lens
  - A large radius allows light to pass through the entire lens



A spectrum of aperture settings, which control the amount of light that enters the lens. The values shown are called the focal ratio or f-stop

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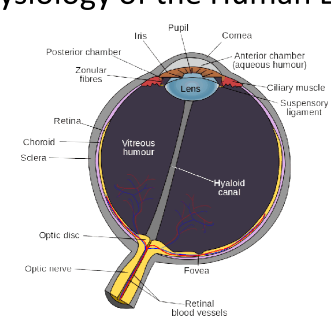
Physiology of Human Vision

Physiology of the Human Eye



This viewpoint shows how the right eye would appear if sliced horizontally (the nose would be to the left)

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Eye Movements

- Eye rotations occur both voluntarily and involuntarily
  - Allows a person to fixate on features in the world, even the head or target features are moving
- A reason for eye movement is to position the feature of interest on the fovea
  - Only the fovea can sense dense, color images, and it unfortunately spans a very narrow field of view
- To gain a coherent, detailed view of a large object, the eyes rapidly scan over it while fixating on points of interest

The trace of scanning a face using saccades

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Eye Movements .

- Another reason for eye movement is that our photoreceptors are slow to respond to stimuli due to their chemical nature
  - They take up to 10ms to fully respond to stimuli and produce a response for up to 100ms
- Eye movements help keep the image fixed on the same set of photoreceptors so that they can fully charge
  - This is similar to the image blurring problem that occurs in cameras at low light levels and slow shutter speeds
- Additional reasons for eye movement are to maintain a stereoscopic view and to prevent adaptation to a constant stimulation
  - It has been shown experimentally that when eye motions are completely suppressed, visual perception disappears completely

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Eye Movements ..

- As movements combine to build a coherent view, it is difficult for scientists to predict and explain how people interpret some stimuli
  - i.e. Optical illusions
    - Next slide

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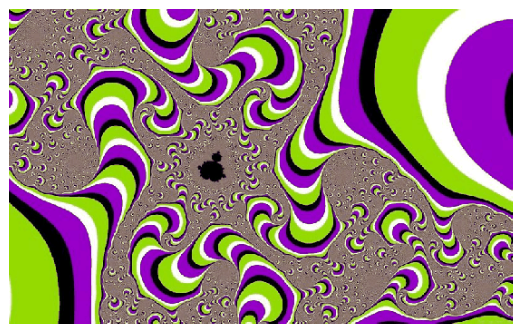
Eye Movements ...



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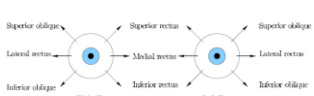
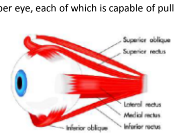
Eye Muscles



There are six muscles per eye, each of which is capable of pulling the pupil toward its location



The six muscle tendons attach to the eye so that yaw, pitch, and a small amount of roll become possible

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Quality of the VR Visual Display

- Three crucial factors for the display are:
  - Spatial resolution
    - How many pixels per square area are needed?
  - Intensity resolution and range
    - How many intensity values can be produced, and what are the minimum and maximum intensity values?
  - Temporal resolution
    - How fast do displays need to change their pixels?

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HMDs

Introduction to HMDs

- Different categories exist
- Worn on the head or as part of a helmet
- HMDs have a small display optic in front of eye(s)
  - Monocular HMD
  - Binocular HMD

VR Technical Approaches

- Head-Mounted
  - Head-mounted wide-view stereo display
- Cave-based
  - Walls of a room are rear-projection stereo displays
  - The user wears goggles to enable viewing in 3D
- Other-type
  - Hand held, or hand moved, display
  - Position and orientation are tracked

HMD Depth Perception

- Depth perception requires different images for the left and right eyes
  - Not all HMDs provide depth perception
  - Some lower-end modules are essentially bi-ocular devices where both eyes are presented with the same image

https://en.wikipedia.org/wiki/Head-mounted_display

HMD Depth Perception .

- Multiple configurations exist:
  - Dual video inputs
    - Providing a completely separate video signal to each eye
  - Time-based multiplexing
    - Methods such as frame sequential combine two separate video signals into one signal by alternating the left and right images in successive frames
  - Side by side or top-bottom multiplexing
    - This method allocated half of the image to the left eye and the other half of the image to the right eye

https://en.wikipedia.org/wiki/Head-mounted_display

HMD Performance Parameters

- Ability to show stereoscopic imagery
  - A binocular HMD has the potential to display a different image to each eye
  - This can be used to show stereoscopic images
  - This is the distance at which, given the average human eye rangefinder "baseline" (distance between the eyes or Interpupillary distance (IPD)) of between 2.5 and 3 inches (6 and 8 cm), the angle of an object at that distance becomes essentially the same from each eye

https://en.wikipedia.org/wiki/Head-mounted_display

HMD Performance Parameters .

- Interpupillary distance (IPD)
  - This is the distance between the two eyes, measured at the pupils, and is important in designing HMDs
- Field of view (FOV)
  - Humans have an FOV of around 180°, but most HMDs offer far less
  - Typically, a greater field of view results in a greater sense of immersion and better situational awareness
  - Most people do not have a good feel for what a particular quoted FOV would look like (e.g., 25°) so often manufacturers will quote an apparent screen size
  - Consumer-level HMDs typically offer a FOV of about 30-40° whereas professional HMDs offer a field of view of 60° to 150°.

https://en.wikipedia.org/wiki/Head-mounted_display

HMD Performance Parameters ..

- Resolution
  - HMDs usually mention either the total number of pixels or the number of pixels per degree
  - Pixel density is also used to determine visual acuity
  - HMDs typically offer 10 to 20 pixels/°
- Binocular overlap
  - Measures the area that is common to both eyes
  - Binocular overlap is the basis for the sense of depth and stereo, allowing humans to sense which objects are near and which objects are far
    - Humans have a binocular overlap of about 100° (50° to the left of the nose and 50° to the right)
    - The larger the binocular overlap offered by an HMD, the greater the sense of stereo

https://en.wikipedia.org/wiki/Head-mounted_display

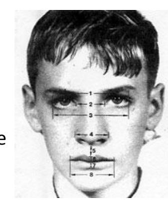
HMD Performance Parameters ...

- Distant focus (collimation)
  - Optical methods may be used to present the images at a distant focus
    - Seems to improve the realism of images that in the real world would be at a distance
- On-board processing and operating system
  - Some HMDs offer on-board OS (i.e. Android) allowing applications to run locally on the HMD
    - Eliminating the need to be tethered to an external device to generate video
  - These are sometimes referred to as smart goggles

https://en.wikipedia.org/wiki/Head-mounted_display

Interpupillary Distance (IPD)

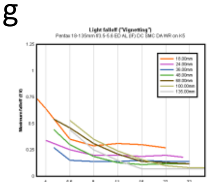
- IPD is the distance between the center of the pupils of the two eyes
- It is critical for the design of binocular viewing systems
  - Because both eye pupils need to be positioned within the exit pupils of the viewing system
- Viewing systems include
  - Binocular microscopes, night vision devices or goggles (NVGs), and head-mounted displays (HMDs)



https://en.wikipedia.org/wiki/Interpupillary_distance

Vignetting

- In optics, vignetting is a reduction of an image's brightness or saturation at the periphery compared to the image center
- An unintended and undesired effect caused by camera settings or lens limitations

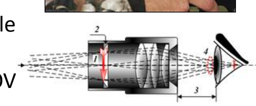


Example of vignetting characteristics dependent on focal length

https://en.wikipedia.org/wiki/Vignetting

Eye Relief

- The eye relief of an optical instrument (i.e. telescope, microscope, binoculars) is the distance from the last surface of an eyepiece at which the user's eye can obtain the full viewing angle
- If a viewer's eye is outside this distance, a reduced FOV will be obtained
- The calculation is complex



Optics showing eye relief and exit pupil.
(1) Real image, (2) Field diaphragm
(3) Eye relief, (4) Exit pupil

https://en.wikipedia.org/wiki/Eye_relief

HMD Peripherals

- The most basic HMDs simply project an image on a wearer's visor (or reticle)
  - The image is not slaved to the real world
    - i.e. the image does not change based on the wearer's head position
- More sophisticated HMDs incorporate a positioning system that tracks the wearer's head position and angle
  - So that the picture or symbology displayed is congruent with the outside world using see-through imagery

https://en.wikipedia.org/wiki/Head-mounted_display

HMD Peripherals .

- Head tracking
  - Slaving the imagery
    - May also be used with tracking sensors that detect changes of angle and orientation
- Eye tracking
  - Measure the point of gaze, allowing a computer to sense where the user is looking
- Hand tracking
  - Tracking hand movement from the perspective of the HMD allows natural interaction with content and a convenient game-play mechanism

https://en.wikipedia.org/wiki/Head-mounted_display

Characteristics of HMDs

- Immersive
  - You are inside the computer world
  - Can interact with real world (mouse, keyboard, people)
- Ergonomics
- Resolution and field of view
- Tethered

Modern HMDs

Video Head-Mounted Display

- Video head-mounted displays accept video from a camera and mix it electronically with computer graphics
  - Easier to perform registration and calibration
  - Watch a digital representation of the world
- Most popular method until now for AR

TriVisio

- Stereo video input
  - PAL resolution cameras
- 2 x SVGA displays
  - 30 degree FOV
  - User adjustable convergence
- $6,000 USD

http://www.trivisio.com/

Vuzix Display - Wrap 1200DXAR

- 4th generation
- 3 DOF head tracker
- Stereoscopic 3D video
- 16:9 or 4:3 aspect ratio
- 1920 x 1080 resolution
- Weighs less than three ounces

https://www.vuzix.com/

Video See Through Example

https://www.youtube.com/watch?v=nEGtha40PUo

Optical Head-Mounted Display

- Nowadays, see-through displays are lightweight with high-resolution optical devices
- However, certain inefficiencies remain such as sufficient:
  - Brightness
  - Resolution
  - Field of view
  - Contrast

Optical Head-Mounted Display

- Various techniques have existed for see-through HMDs and can be summarized into two main families:
  - "Curved Mirror" (or Curved Combiner) based
  - "Waveguide" or "Light-guide" based
- The curved mirror technique has been used by Vuzix in their Star 1200 product, by Olympus, and by Laster Technologies
- Various waveguide techniques have existed for some time
  - These techniques include diffraction optics, holographic optics, polarized optics, and reflective optics

https://en.wikipedia.org/wiki/Optical_head-mounted_display

Waveguide Techniques

- Diffractive waveguide
  - Slanted diffraction grating elements (nanometric 10E-9)
    - Nokia technique now licensed to Vuzix
- Holographic waveguide
  - 3 holographic optical elements (HOE) sandwiched together (RGB)
    - Used by Sony and Konica Minolta
- Polarized waveguide
  - 6 multilayer coated (25–35) polarized reflectors in glass sandwich
    - Developed by Lumus

https://en.wikipedia.org/wiki/Optical_head-mounted_display

Waveguide Techniques .

- Reflective waveguide
  - Thick light guide with single semi reflective mirror
    - This technique is used by Epson in their Moverio product
- "Clear-Vu" reflective waveguide
  - Thin monolithic molded plastic w/ surface reflectors and conventional coatings
    - Developed by Optinvent and used in their ORA product
- Switchable waveguide
  - Developed by SBG Labs

https://en.wikipedia.org/wiki/Optical_head-mounted_display

Google Glass

- Google Glass is based on OHMD technology
  - Displays information in a smartphone-like hands-free format
  - Wearers communicate with the Internet via natural language voice commands
- Available to the public on May 15 2014 for $1,500
  - Stopped on January 15 2015

https://en.wikipedia.org/wiki/Google_Glass

Google Glass Videos

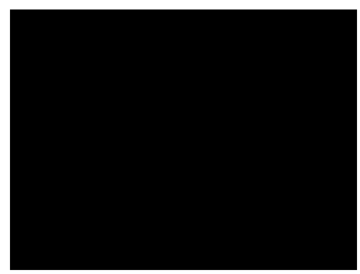
- https://www.youtube.com/watch?v=4_X6EyqXa2s
- https://www.youtube.com/watch?v=y3dGVeW24tc
- https://www.youtube.com/watch?v=JSnB06um5r4

Innovega iOptik System

- It comprises a pair of contact lens which refocus polarized light to the pupil
- Allows the wearer to focus on an image that is as near as 1.25 cm to the eye
- Prototype features a field of view of 60 degrees or more
  - Aiming at 120 degrees FOV
- Designed for military use
  - A consumer version coming soon

http://www.innovega-inc.com/index.php

Innovega iOptik System Video



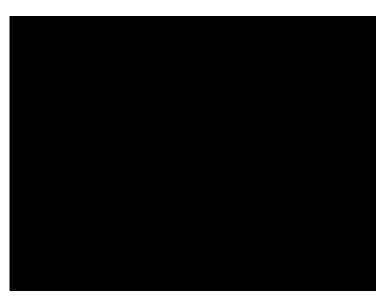
http://www.innovega-inc.com/videos.php

Pinlight Displays

- Wide Field of View Augmented Reality Eyeglasses using Defocused Point Light Sources
- Instead of conventional optics
  - LCD panel
  - An array of point light sources
- Coding allows for miniature see-through projectors

http://pinlights.info/

Pinlight Displays Video



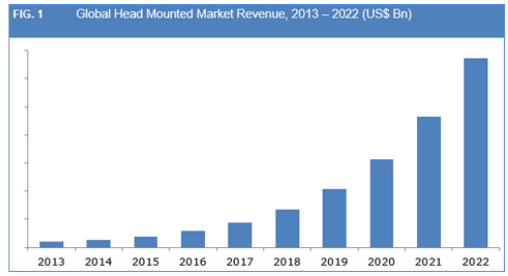
http://pinlights.info/

Comparison of OHMDs Technologies

Combiner technology	Size	Eye box	FOV	Other	Example
Flat combiner 45 degrees	Thick	Medium	Medium	Traditional design	Vuzix, Google Glass
Curved combiner	Thick	Large	Large	Classical bug-eye design	Many products (see through and occlusion)
Phase conjugate material	Thick	Medium	Medium	Very bulky	OdaLab
Buried Fresnel combiner	Thin	Large	Medium	Parasitic diffraction effects	The Technology Partnership (TTP)
Cascaded prism/mirror combiner	Variable	Medium to Large	Medium	Louver effects	Lumus, Optinvent
Free form TIR combiner	Medium	Large	Medium	Bulky glass combiner	Canon, Verizon & Kopin (see through and occlusion)
Diffractive combiner with EPE	Very thin	Very large	Medium	Haze effects, parasitic effects, difficult to replicate	Nokia / Vuzix
Holographic waveguide combiner	Very thin	Medium to Large in H	Medium	Requires volume holographic materials	Sony
Holographic light guide combiner	Medium	Small in V	Medium	Requires volume holographic materials	Konica Minolta
Combo diffuser/contact lens	Thin (glasses)	Very large	Very large	Requires contact lens + glasses	Innovega & EPFL
Tapered opaque light guide	Medium	Small	Small	Image can be relocated	Olympus

https://en.wikipedia.org/wiki/Optical_head-mounted_display

HMD Market

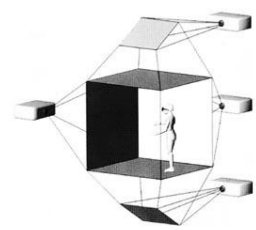


http://www.credenceresearch.com/report/head-mounted-display-hmd-market

CAVE

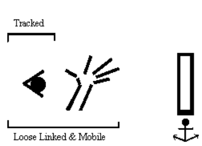
CAVE

- Computer Automatic Virtual Environment (CAVE)
  - One of the most immersive environment

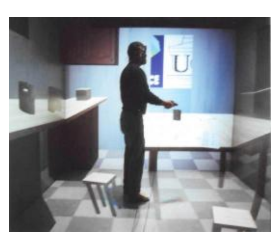


CAVE Characteristics

- Eyes and hands are linked and mobile
- Display is fixed
- Shadow effect problem
  - When another person hides walls, or when an object is supposed to be between two persons



CAVE Examples



CAVE Videos

- https://www.youtube.com/watch?v=STMcWUtQr1Y
- https://www.youtube.com/watch?v=j59JxfbvxGg
- https://www.youtube.com/watch?v=tlBOr524_18

Large Screen Projection

- Larger field-of-view than HMD
- Field of regard is smaller than HMD but larger than a typical CRT Display
- Projectors must be aligned properly

Large Screen Projection Architectures

- Front Projection
  - User may be in the way
- Back Projection
  - Takes up even more space
- When multiple screens are arranged at or near 90 degree angles, reflection between screens may be a problem

Large Screen Projection Pros

- Viewer not isolated from real objects or other people in the virtual world space
- Less physical gear to wear than HMD
- Potentially better resolution than HMD
- Large field of view compared to HMD or CRT

Large Screen Projection Cons

- Usually one person is head-tracked
- Real objects may occlude virtual objects in inappropriate ways
- Multiple screens require more computation
- At least one direction is not part of the virtual world
- Lighting

Large Screens Videos

- https://www.youtube.com/watch?v=oNAl0RGBLCA
- https://www.youtube.com/watch?v=RspO9rImJuw

Other Displays

Small Area Displays

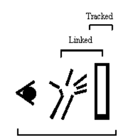
- Small area displays are portable and thus be suitable for many VR applications
- The major disadvantages of these displays are the limited working area and resolution
  - Getting better!
- Small area displays have also illumination problems

Hand Held VR

- Hand-held computing devices are ubiquitous
  - Have become part of our lives
  - Also increasingly being equipped with special sensors and non-traditional displays

Typical Characteristics

- Hands and display are tightly coupled
  - All three are mobile
- Problems
  - All of HMD and CAVE systems



Pico Projectors

- Extra small projectors
  - Microvision, 3M, Samsung, Philips

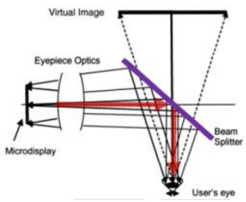
http://www.mvis.com/

Head Mounted Projector

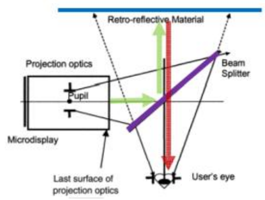
- Retro-reflective Material
- Potentially portable
- NVIS P-50 HMPD
  - 1280x1024/eye
  - Stereoscopic
  - 50 degree FOV

http://www.nvis.com/

HMD vs HMP



Head Mounted Display



Head Mounted Projector

Conclusions

- Many technologies exist
  - Depending on the application different solution
- HMDs are dominating at the moment
  - Becoming cheaper
  - More immersive

Questions