PA198
Augmented Reality Interfaces

Lecture 3
Augmented Reality Displays

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12th October 2015

The Eye

Basic Eye

Cornea
Crystalline Lens
Fovea
Retina
Optic Nerve

Properties of the Eye

• Approximate Field of View
  – 120 degrees vertical
  – 150 degrees horizontal (one eye)
  – 200 degrees horizontal (both eyes)

• Acuity
  – 30 cycles per degree (20/20 Snellen acuity)

The Eye

• Accommodation describe the altering of the curvature of the crystalline lens by means of the ciliary muscles
  – Expressed in diopters

• Retina is the sensory membrane that lines the back of the eye and receives the image formed by the lens of the eye

• Fovea is the part of the human retina that possesses the best spatial resolution or visual acuity

Field of View (FOV)

• The FOV the user can achieve at a given eye location limited by vignetting of off axis field angles

• This will be limited by the eye relief and the FOV of the system

Sherman & Craig, pp. 151-159
FOV limitations

- Eye must rotate to view off axis field angles
  - Eye point of rotation located 10mm behind pupil
  - Will cause translation of pupil
    - As the eye translates out of Eye Box the user will move eye closer to the system (effectively decreasing the Eye Relief)

Monocular Field-of-View

- FOV may be measured horizontally, vertically or diagonally
- Monocular FOV is the angular substance of the displayed image as measured from the pupil of one eye
  - Usually expressed in degrees

Binocular Field-of-View

- Total FOV is the total angular size of the displayed image visible to both eyes
- Binocular FOV refers to the part of the displayed image visible to both eyes
  - Also known as stereoscopic FOV

Focal Length

- The focal length of an optical system is a measure of how strongly the system converges or diverges light
- Represents the distance from the surface of a lens (or mirror) at which rays of light converge

Optics Characteristics

Diopter

- The power of a lens is measured in diopters
  - Where the number of diopters is equal to:
    - \(1/(\text{focal length of the lens measured in meters})\)
- The main benefits over focal length
  - The lensmaker’s equation has the object distance, image distance, and focal length all as reciprocals
  - When relatively thin lenses are placed close together their powers approximately add
Contrast Transfer Function (CTF)

• CTF: measurement of contrast for a given spatial frequency square wave pattern

\[
\text{Contrast (frequency)} = \frac{\text{Max} - \text{Min}}{\text{Max} + \text{Min}}
\]

Example of square wave pattern displayed by HMD

CTF Depends on Pupil Position

• Horizontal and Vertical CTF both measured as function of pupil position
• Cutoff at 50% of CTF at ideal pupil position

Ocularity

• Ocularity is another criterion for categorising HMDs:
  — Monocular
    • HMD image goes to only one eye
  — Biocural
    • Same HMD image to both eyes
  — Binocular (stereoscopic)
    • Different but matched images to each eye

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)

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

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
Eye Relief Effect on Viewable FOV

- Pupil placed at ER resulting in vignetting of off-axis field angles (lose FOV at edges)
- Eye point of rotation placed at ER resulting in reduced clearance between user's eye and the HMD, but vignetting minimized

Image-Forming Optical System

- An image-forming optical system is a system capable of being used for imaging
- The diameter of the aperture is a common criteria for comparison among optical systems — i.e. Large telescopes
- The traditional systems are:
  - Mirror-systems (catoptrics) - has a focal point
  - Lens-systems (dioptrics) - has a focal point
  - Optical fiber - transfers an image from one plane to another without an optical focus

Image-forming optical system [link to Wikipedia]

Simple Magnifier HMD Design

- Eyepiece (one or more lenses)
- Display (Image Source)

Thin Lens Equation

\[ \frac{1}{p} + \frac{1}{q} = \frac{1}{f} \]

- where
  - \( p \) = object distance
    - Distance from image source to eyepiece
  - \( q \) = image distance
    - Distance of image from the lens
  - \( f \) = focal length of the lens

Thin Lens Equation Conventions

- If the incident light comes from the object, we say it is a real object, and define the distance from the lens to it as positive
  - Otherwise, it is virtual and the distance is negative
- If the emergent light goes toward the image, we say it is a real image, and define the distance from the lens to it as positive
  - \( f \) = positive for a converging lens
- A light ray through the center of the lens is undeflected

Sherman & Craig, pp. 151-159

Formulas

- Visual Resolution in Cycles per degree
  - \( \text{(Vres)} = \frac{\text{Number of pixels}}{2 \times \text{FoV in degrees}} \)
- Example
  - \( \frac{1024 \text{ pixels per line}}{2 \times 40 \text{ degrees}} = \text{Horizontal resolution of 12.8 cycles per degree} \)
- To convert to Snellen acuity (as in 20/xx)
  - \( \text{Vres} = 600/xx \)
  - So: \( \text{Vres} = 600/12.8 \) (20/47)

Sherman & Craig, pp. 151-159
**Large Expanse Extra Perspective (LEEP)**

- LEEP provides extreme wide-angle stereoscopic optics used in photographic and virtual reality systems
- Higher resolution (more pixels) in the middle of the field of view, lower resolution on the periphery
- Pincushion distortion

![LEEP Optical Viewer](https://en.wikipedia.org/wiki/Large_Expanse_Extra_Perspective)

**LEEP Standard**

- **VIRTUAL REALITY TECH TIP FROM LEEP**
- LEEP Anamorphic Projection Gives Higher Resolution
- **VIRTUAL SCREEN vs. REAL SCREEN VS. FOLLOW UP SCREEN**
- **HIGH RESOLUTION WITH SMALLER PIXELS**
- **PIXELS MUST BE MODIFIED TO BEST VIEW LIFE-SIZE VIEWING**


**Fresnel Lens**

- Lenses of large aperture and short focal length without the mass and volume of material (That would be required by a lens of conventional design)
- Can be made much thinner than a comparable conventional lens (i.e. Using a flat sheet)
- A Fresnel lens can capture more oblique light from a light source (Thus allowing the light to be visible over greater distances)
- More even resolution distribution
- Less distortion

![Fresnel Lens](https://en.wikipedia.org/wiki/Fresnel_lens)

**Relationship Between Angle and Screen distance**

![Graph](http://www.leepvr.com/sid1992.php)
Distortion in LEEP Optics

A rectangle

Maps to this

Camera Calibration

To Correct Distortion

- Must pre-distort image
- This is a pixel-based distortion
- Graphics rendering uses linear interpolation
- Too slow on most systems

Distorted Field of View

- Your computer graphics model assumes some field of view
- Scan converter may overscan or underscan
  - Not all of your graphics image may appear on the screen
- Problem
  - Are the display screens aligned perpendicular to your optical axis?

Collimated (o=f)

- Optical collimators can be used to:
  - Calibrate other optical devices
  - Check if all elements are aligned on the optical axis
  - Set elements at proper focus
  - Align two or more devices such as binoculars or gun barrels and gunsights
- If the image source is placed at the focal point of the lens, then the virtual image appears at optical infinity
  - $1/p + 1/q = 1/f$  $q = \infty$, if $p=f$

Distorted Field of View Example

Distance along $z$-axis

Sherman & Craig, pp. 151-159

Sherman & Craig, pp. 151-159

Sherman & Craig, pp. 151-159

https://en.wikipedia.org/wiki/Collimator
**Compound Microscope HMD Design**

- Relay lens produces a real image of the display image source (screen) at some intermediate location in the optical train.
- The eyepiece is then used to produce an observable virtual image of this intermediate image.

**Exit Pupil**

- The area in back of the optics from which the entire image can be seen.
  - Important if IPD not adjustable, mount not secure.
- Compound microscope optical systems have a real exit pupil.
- Simple magnifier optical systems do not have an exit pupil.

**Displays**

**Visually Coupled Systems**

- Integration of the natural visual and motor skills of a user into the system that is controlling.
- Basic components include:
  - An immersive visual display
    - HMD, large screen projection (CAVE), dome projection, etc.
  - A means of tracking head and/or eye motion.
  - A source of visual information that is dependent on the user’s head/eye motion.

**AR Displays Classification**

- The most popular classification of display technologies can be categorized into:
  - Head mounted devices
    - Head up display (HUD)
    - Head mounted display (HMD)
    - Head Mounted Projector (HMP)
  - Non-head mounted devices
- Another one is split into (see next slide):
  - Indoors
  - Outdoors
Heads-Up Displays

HUD Generations

• First Generation
  – Use a CRT to generate an image on a phosphor screen, having the disadvantage of the phosphor screen coating degrading over time
  – The majority of HUDs in operation today are of this type
• Second Generation
  – Use a solid state light source, for example LED, which is modulated by an LCD screen to display an image
  – These systems do not fade or require the high voltages of first generation systems
  – These systems are on commercial aircraft

HUD for Car Video

Head-Mounted Displays
**Head Mounted Displays**

- Optical System
- Image Source
  - CRT or Flat Panel (LCD)
- See-through or non see-through
- Mounting Apparatus
- Earphones
- Position Tracker

**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

**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

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Video See Through Example

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

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

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

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
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


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/

Comparison of OHMDs Technologies

<table>
<thead>
<tr>
<th>Combiner technology</th>
<th>Eye</th>
<th>Eyepiece</th>
<th>FOV</th>
<th>Other</th>
<th>Example</th>
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</thead>
<tbody>
<tr>
<td>Flat combiner</td>
<td>Thin</td>
<td>Medium</td>
<td>Medium</td>
<td>Traditional design</td>
<td>Vuzix, Google Glass</td>
</tr>
<tr>
<td>Curved combiner</td>
<td>Thick</td>
<td>Large</td>
<td>Large</td>
<td>Classical bug-eye design</td>
<td>OdaLab</td>
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<tr>
<td>Phase conjugate material</td>
<td>Thin</td>
<td>Medium</td>
<td>Medium</td>
<td>Tiny crystal</td>
<td>The Technology Partnership (TTI)</td>
</tr>
<tr>
<td>Buried Fresnel combiner</td>
<td>Very thin</td>
<td>Medium to large</td>
<td>Medium</td>
<td>Large in H</td>
<td>Lumus, Optinvent</td>
</tr>
<tr>
<td>Free form TIR combiner</td>
<td>Medium</td>
<td>Large</td>
<td>Medium</td>
<td>Very thin</td>
<td>The Technology Partnership (TTI)</td>
</tr>
<tr>
<td>Diffractive combiner with EPE</td>
<td>Very thin</td>
<td>Very large</td>
<td>Very large</td>
<td>Haze effects, parasitic effects</td>
<td>Nokia / Vuzix</td>
</tr>
<tr>
<td>Holographic light guide combiner</td>
<td>Medium</td>
<td>Small in V</td>
<td>Medium</td>
<td>Requires volume holographic materials</td>
<td>Konica Minolta</td>
</tr>
<tr>
<td>Tapered opaque light guide</td>
<td>Medium</td>
<td>Very large</td>
<td>Very large</td>
<td>Image can be relocated</td>
<td>Olympus</td>
</tr>
</tbody>
</table>

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

Bionic Contact Lenses

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

Non-Heads Mounted Displays

- The most common non-head mounted displays can be categorised as:
  - Small Area Displays
  - Large Area Displays
  - Spatial 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
Small Area Displays

- Three basic configurations:
  - Front projection
  - Back projection
  - Conventional monitors
    - CRTs, LCDs, Touchscreens and Plasma
- Users must use 3D glasses or HMDs
- The most significant disadvantage of large screen displays is the limited area of operation
  - i.e. Limited movement

Large Area Displays

- ImmersaDesk
- CAVE System

AR for Large Screens Video

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

Spatial Displays

- In contrast to small area displays, spatial displays isolate most of the technology from the user and integrate it into the environment
- Large screens and spatially immersive displays extend the idea of ImmersaDesk using multiple projection screens and can be used to create a very effective and immersive experience
Spatial Displays

- Nothing to wear and/or carry
- Uses digital projectors to display information
- Marker-based and markerless devices

[Images of AR Phone Keypad and AR Keyboard]

Spatial AR Video

[Video link: https://www.youtube.com/watch?v=D7fZAYV4a]

Pico Projectors

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

[Image of Pico Projector]

MIT Sixth Sense

- Comprised of a pocket projector, a mirror and a camera
- $350 to build

[Images of MIT Sixth Sense devices]

AR Haptic Workbench

[Diagram of AR Haptic Workbench]

AR Types
Monitor-based AR

- Simplest available
- Treat laptop/PDA/cell phone as a window through which you can see AR world

Advantages of Monitor-based AR

- Consumer-level equipment
- Most practical
- A lot of current research aimed here
- Other current active area is a flip-down optical display

Video See-Through AR

Advantages of Video See-Through AR

- Flexibility in composition strategies
- Real and virtual view delays can be matched
- True occlusion
- Wide FOV is easier to support

Disadvantages of Video See-Through AR

- Not easy to make ‘good’ quality photorealistic graphic scenes
- Can be more expensive

Optical See-Through AR
Advantages of Optical See-Through AR

• Safety
• Light weight
• Simplicity (cheaper)
• Resolution
• No eye offset

Disadvantages of Optical See-Through AR

• Prone to lighting conditions
• Registration much harder!
• Optics are not yet there

Other AR Types

Eye Multiplexed AR Approach

• Let users combine the views of the two worlds mentally in their minds
  – The virtual scene is registered to the physical environment
  – The rendered image shows the same view of the physical scene that the user is looking at
• However, the rendered image is not composited with the real world view
  – Up to the user to mentally combine the two images in their minds
Alternate Displays

Virtual Showcase

- Mirrors on a projection table
  - Head tracked stereo
  - Up to 4 users
  - Merges graphic and real objects
  - Exhibit/museum applications
- Fraunhofer Institute (2001)

Augmented Paleontology

Questions

Acknowledgements

- Special Thanks to Prof. Mark Billinghurst