Optics & Displays
CS 294-10: Virtual Reality & Immersive Computing
EECS, UC Berkeley
Fall 2017

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Books (Optional Reading)


Recall: AR/VR System Components

• Sense
  – Accurate spatio-temporal position tracking and localization (inertial measurement unit, cameras, microphones, …)

• Compute
  – High-performance and power-efficient hardware and software for real-time processing, rendering, and display

• Display
  – Spatial light modulation for immersive 3D visual experience

• Audio
  – 3D immersive sound experience

• Interactions
  – Human inputs and interfaces
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The Stereoscope, invented by Sir Charles Wheatstone in 1833
Improved construction by Oliver Wendell Holmes. Widely popular in late 1800s to early 1900s.
View of Boston, c. 1860

Modern-Day VR Display Examples

- **Oculus Rift and HTC Vive**
  - 2160X1200 pixels @461-PPI resolution
  - 90-FPS refresh rate
  - 110° FOV

- **Samsung Gear VR (with Galaxy S7)**
  - 2560X1440 pixels @577-PPI resolution
  - 60-FPS refresh rate
  - 96° FOV
Key Display Requirements

• Immersive visual experience
  – 3D image display
  – Wide field of view (FOV)
  – High pixel density (resolution) and fill factor

• Low-latency visual perception
  – High frame refresh-rate, global refresh
  – Fast pixel response time, low persistence

• Visual and ergonomic comfort
  – High contrast, brightness, and uniformity
  – Low weight, comfortable design
Pixels

Physical RGB Sub-Pixels Convention

Resulting Logical Square Pixel
Resolution and Field-of-View (FOV)

- For head-mounted display (HMD) applications, pixels-per-degree (PPD) is a more appropriate measure of resolution than pixels-per-inch (PPI) that is typical in describing screen resolution.

- The human-eye has an angular resolution of about 1/60th of a degree at the central vision.

- Each eye has a horizontal field-of-view of ~160° and a vertical field-of-view of ~175°. The two eyes work together for stereoscopic depth perception over ~120° wide and ~135° high FOV.

<table>
<thead>
<tr>
<th></th>
<th>PPD required</th>
<th>Horizontal FOV (deg)</th>
<th>Equivalent horizontal Kpixels</th>
<th>Vertical FOV (deg)</th>
<th>Equivalent vertical Kpixels</th>
<th>Total Mpixels required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Each eye</td>
<td>60</td>
<td>160</td>
<td>9.6</td>
<td>175</td>
<td>10.5</td>
<td>~100</td>
</tr>
<tr>
<td>Stereo vision</td>
<td>60</td>
<td>120</td>
<td>7.2</td>
<td>135</td>
<td>8.1</td>
<td>~60</td>
</tr>
</tbody>
</table>

Latencies

• A key system-level parameter for VR/AR/MR devices is “motion-to-photon latency”
  – Delay between the onset of user-motion to emission of photons from the last pixel of the corresponding image frame
  – It’s the sum of the time taken by sensor data acquisition and processing, interfaces, computations, and display updates
  – Desired to be less than 20ms

• Display refresh rate and response time typically dominate the delay time
  – Display refresh rate: 60Hz inadequate, 90Hz prevalent, but desire 120Hz or higher
  – Require low pixel persistence
Viewing Optics: Key Considerations

- Eye Box
  - ~12mm X 12mm desired (~4mm pupil + ~6mm eye rotation + ~2mm tolerance for viewing comfort)

- Eye Clearance
  - ~20mm recommended for consumer applications (accommodate prescription glasses)

- Size/Weight/Form-Factor
  - Lighter and stylist consumer designs
See-Through Displays for AR: Examples (Details in Backup Slides)

Amitai, Mukawa, Levola, Cakmakci
Spatial Light Modulators: Liquid Crystal Displays (LCD)
LCD Pixel Driving Architecture
Cross-section of a typical LCD

- Exit polarizer
- Compensator film
- Top glass substrate
- Color filters
- Top electrode
- Top alignment layer
- Liquid crystal
- Bottom alignment layer
- Bottom electrode
- Thin-film transistors
- Bottom glass substrate
- Compensator film
- Entrance polarizer
- Brightness enhancement films
- Diffuser
- Backlight
Let’s just focus on the main elements to understand how LCD works…

- Entrance polarizer: Transmits only one polarization of light.
- Liquid crystal: Birefringent layer alters the polarization as the electric field changes the effective refractive index.
- Color filter: Selectively absorbs undesired wavelength to produce color image.
- Exit polarizer: Blocks or partially/fully transmits light depending on the polarization.
- Top electrode: 
- Bottom electrode: 
- Light:
At the “heart” of the LCD: Liquid crystal molecules

An example:
Liquid crystal molecules

Chemist’s view:

\[
C_4H_9 - N = CH - C_6H_4 - O - CH_3
\]

Methoxybenzilidene Butylanaline ("MBBA")

\[
C_{10}H_{21} - O - CH = CH - C = CH - CO - CH_3 - C_2H_5
\]
p-decyloxybenzilidene p’-amino 2-methylbutylcinnamate ("DOBAMBC")

Physicist’s view:

~5 Å

~20 – 30 Å

This type of liquid crystals are called the “rod-like” molecules, commonly used as the electro-optical material in LCDs.
Effect of electric field on Liquid Crystal molecules

The torque experienced by rod-like liquid crystal molecules due to the electric dipole-field interaction aligns them along the direction of the electric field.

The disc-like molecules align perpendicular to the electric field.
A brief look at the history of LCD

Good references:


Friedrich Reinitzer, an Austrian botanist, first observed liquid crystals in 1888, when he discovered that cholesteryl benzoate exhibits a mesophase between solid state and liquid state.

Otto Lehmann, in 1889, discovered that the mesophase exhibited a double refraction effect like a crystal, and named it “fliessende krystalle” or the “liquid crystal”.
Aligning liquid crystal molecules

Construction of a liquid crystal device requires aligning the molecules in specific directions in between the substrates, thus inventing the processes to accomplish this was a major step.

The method widely used throughout the industry is to coat polyimide on the ITO covering the glass and then rub with cotton cloth.

The origin of this rubbing technique goes back to 1928, due to H. Zocher.

AFM micrographic picture of polyimide surface before and after rubbing, from a 1992 study by T. Uchida et al.
Birth of the LCD

Vsevolod Freedericksz, in 1931, discovered periodic hydrodynamic domains in liquid crystals subjected to electric fields. Richard Williams of RCA, in 1962, discovered the “Williams domains”. These effects demonstrated the feasibility of liquid crystals as electro-optical elements for display devices.

George Heilmeier of RCA, in 1964, invented the LCD, by discovering the “guest-host mode” and “dynamic scattering mode” and demonstrating devices.
Discovery of the Twisted Nematic (TN) mode

Wolfgang Helfrich with Martin Schadt, in 1970, demonstrated the TN mode, the most prominent liquid crystal mechanism for decades to come, thereby arguably establishing the basis of the modern LCD industry. The early idea of TN structure is traced back to Charles Mauguin in 1911.

Helfrich in 1976

Results from the historic 1971 paper by Helfrich and Schadt
The first commercial devices

In 1973, Sharp announced and subsequently introduced the Elsi Mate EL-805 pocket calculator, the first commercial liquid crystal device. In 1975, Sharp developed the Magic Mirror Clock. Both were based on DSM.

Seiko, in 1973, introduced the first digital liquid-crystal watch, using TN mode.
Concept of the Active-Matrix Drive

In 1971, Bernard Lechner et al. proposed the idea of using an array of Thin-Film Transistors (TFTs) to control cells operating in DSM.

As shown in the figure below, they even conceived the idea of an external storage capacitor! This pixel driving configuration is still in use in modern LCDs.

AM circuit with external storage capacitor proposed by Lechner et al.
Optics of LCD

**C. H. Gooch** and **H. A. Tarry**, in 1974, derived the famous optical transmission equations for the TN mode liquid crystal display.

We will look into it later in this class.

Transmission of the “normally black” TN display, from Gooch and Tarry’s historic 1974 paper
Optics of LCD
JAMES CLERK MAXWELL
1831-1879

“One scientific epoch ended and another began with James Clerk Maxwell”

- Albert Einstein
The equations of optics are Maxwell’s equations

\[ \begin{align*}
\nabla \cdot \vec{E} &= \frac{\rho}{\varepsilon} \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \cdot \vec{B} &= 0 \\
\nabla \times \vec{B} &= \mu \varepsilon \frac{\partial \vec{E}}{\partial t}
\end{align*} \]

\[ \vec{E}^{\nabla^2} - \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \]

“Wave” equation

where \( \vec{E} \) is the electric field, \( \vec{B} \) is the magnetic field, \( \rho \) is the charge density, \( \varepsilon \) is the permittivity, and \( \mu \) is the permeability of the medium.
An Electromagnetic Wave

The electric and magnetic fields are in phase.

\[ \vec{E}(x, t) = E_0 \exp(i(kx - \omega t)) \]

The electric field, the magnetic field, and the k-vector are all perpendicular:

\[ \vec{E} \times \vec{B} \propto \vec{k} \]
An Electromagnetic Wave
Typically, the speed of light, the wavelength, and the amplitude decrease, but the frequency, $\omega$, doesn’t change.
Absorption Coefficient and the Irradiance

The irradiance is proportional to the (average) square of the field.

\[ I = E \cdot E^* \]

Since \( E(z) \propto \exp(-\alpha z/2) \), the irradiance is then:

\[ I(z) = I(0) \exp(-\alpha z) \]

where \( I(0) \) is the irradiance at \( z = 0 \), and \( I(z) \) is the irradiance at \( z \).

Thus, due to absorption, a beam’s irradiance exponentially decreases as it propagates through a medium.
Polarization of Light
Linearly Polarized Light

The light wave shown above has its Electric field vector oscillating purely along one axis (y-axis)

The oscillating Electric field vector of this light wave lies in one single plane (yz-plane)

This wave is “linearly polarized” along y-axis
Visualizing Polarization

“Look into” the wave as if it is propagating towards you, trace the tip of the E-field vector

In the case of the wave shown above

Linearly polarized along y-axis
Unequal arbitrary-relative-phase components yield “elliptical polarization”

E-field variation over time (and space)

Elliptical polarization is the general case of polarized light
Homogenous LC cell:
Substrates rubbed along the same axis
Homogenous cell: effect of electric field

No applied electric field

High electric field
Twisted LC cell:
Substrates rubbed in the perpendicular directions
Twisted cell: effect of electric field

No applied electric field:
Molecules are uniformly twisted

High electric field:
Molecules are untwisted
The “normally-black” 90° TN display

Unpolarized light

Entrance polarizer along x direction
Twisted Nematic LC cell; no electric field
Exit polarizer along x direction

“Dark state” of the display
The transmittance, ratio of output to input light intensity, is given by:

\[
T = \frac{I_0}{I_i} = \frac{\sin^2 \left( \frac{\pi \sqrt{1+u^2}}{2} \right)}{2 \left( 1 + u^2 \right)}
\]

Where,

\[
u = \frac{2(n_e - n_0)l}{\lambda}
\]
So, is the “normally-black” 90° TN display really always black?

The transmittance is zero only for specific values of $u$, leading to the various minima conditions.

However, the transmittance is generally very small when $u$ becomes large.
Maximizing Contrast

\[
T = \frac{I_0}{I_i} = \frac{\sin^2\left(\frac{\pi}{2} \sqrt{1+u^2}\right)}{2(1+u^2)}
\]

\[
u = \frac{2(n_e - n_0)l}{\lambda}
\]

The transmission is zero (minimized), when the argument of \( \sin \) in the numerator is an integral multiple of \( \pi \).

\[
\frac{\pi}{2} \sqrt{1+u^2} = m\pi \quad \Rightarrow \quad u = \sqrt{4m^2 - 1} \quad \text{where } m \text{ is an integer.}
\]

This corresponds to \( u = \sqrt{3}, \sqrt{15}, \sqrt{35} \) for the first, second, and third minimum conditions.

The cell is typically optimally designed for green light (e.g., \( \lambda = 550\text{nm} \))
The 90° TN display with high electric field

Unpolarized light

Entrance polarizer along $x$ direction

Twisted Nematic LC cell; high electric field

Exit polarizer along $x$ direction

"Bright state" of the display
Transmission of Normally-Black mode

Consider $\Delta nd = 0.48 \ \mu m$, which corresponds to the 1$^{st}$ minimum of a normally black TN display at field-OFF state for green light at $\lambda = 550$nm.
Transmission of Normally-White mode
Spatial Light Modulators: Organic Light Emitting Diode (OLED)
LCD vs. OLED
Organic Light Emitting Diode (OLED) Displays

5–10 V

Cathode

Electron

Exciton formation by electron–hole recombination $\rightarrow$ light emission

Anode

Hole

Glass substrate
Organic Light Emitting Diode (OLED) Displays

Diagram of OLED display layers:
- Cathode (opaque)
- Electron transportation layer
- Emission layer
- Hole transportation layer
- Hole injection layer
- ITO anode (transparent)

Current flow:
- 5–10 V
- Emission
Organic Light Emitting Diode (OLED) Displays
White & RGB OLEDs
OLED Driving (Typical)
3D Displays
Recall:
Visual Cues for Depth Perception

• Binocular disparity
• Oculomotor cues
• Motion cues
• Pictorial cues
Recall: Binocular Disparity

(a) Far finger and near finger. For left eye, near finger covers far finger.

(b) Right eye closed. Left eye closed. For right eye, both near and far fingers are visible.
Anaglyph 3D (Red & Cyan Transmissive Filters)
Achromatic Glasses

(a) Passive
Polarized glasses

(b) Active
Electronic shutter glasses synced to TV

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Autostereoscopic 3D Displays (No Glasses)
Towards “True” 3D Visual Experiences: “Light-Field Displays”

• Stereopsis
  – Each eye sees a different perspective view

• Relative motion
  – An eye sees a different view as the viewer’s position is changed

• Focus
  – Consistent accommodation-convergence and focus/blur cues

Convergence-Accommodation Mismatch

A

Real world

Vergence distance
Focal distance

B

3d display

Vergence distance
Focal distance

Display screen

M. Banks, Berkeley
In VR headsets, the lens is placed so that the screen appears to be infinitely far away.
Adjusting Accommodation with Tunable Lens

Electrode structure of a tunable LC lens. Right: expanded view of the region shown within the rectangle of the left picture.

LC lens with voltage applied to provide 400mm focal length  
LC lens with zero volts applied  
Glass lens with 400mm focal length for comparison

P. Bos, L. Li, D. Bryant, A. Jamali, A. Bhowmik, SID 2016
Eye Gaze Tracking

The first and sometimes the fourth Purkinje images of an IR light source are used for eye tracking.

The first Purkinje image generates a bright reflection.

Additional benefit of eye-gaze tracking in the future: **foveated rendering** to substantially reduce the graphical computation workload!
Parting Thoughts…

• Key requirements are relatively well-understood.

• Lots of progress recently in the development of technologies and components, but challenges still remain to be solved.

• Ingredients are important, but end-to-end integration (hardware, software, system, interfaces) is critical.

• Commercial success will hinge on delivering compelling applications with natural user experiences.
Unfortunately no one can be told what the matrix is. You have to see it for yourself.
Backup Slides:

Examples of Optics for See-Through Head-Worn Displays (HWD) in Augmented/Mixed Reality Systems & Screen-Door Effect Reduction
Comfort

- Resolution/weight/CG
- Focus/vergence
- Brightness/contrast
- Ghosts, pupil swim

Immersion

- User IPD coverage
- Untethered
- Display and sensors lag
- 3D world locking
- HDR

- FOV
- World locked spatial audio
- Foveation, peripheral display
- Hard edge occlusion
- Active dimming
- Gesture sensing

Ultimate MR experience
Hardware choices for HoloLens V1
HoloLens Sensor Bar

- Depth Camera
- 2MP Photo / HD Video Camera
- 4 Environment Understanding Cameras
HoloLens Optics and IMU

See-Through Lenses (waveguides)

IMU

HD 16:9 Light Engines
HoloLens MLB (Main Logic Board)

- Windows 10
- Custom-built Microsoft Holographic Processing Unit (HPU 1.0)
- 64GB Flash
- 2GB RAM (1GB CPU and 1GB HPU)
- x86 architecture
HoloLens Spatial Sound

also 4 microphones for speech/beamforming
Dual eye DMA
(not including illumination optics)
The Waveguide Module Assembly (WMA)
Finalized OMA
Spitzer. Eyeglass Display Lens System Employing Off-Axis Optical Design.
US 6,353,503
Mar. 5, 2002

Bettinger. Spectacle-mounted ocular display apparatus.
US 4,806,011
Feb. 21, 1989

HWD Examples (Slide 2 of 18)

Hoshi et al. Off-axial HMD optical system consisting of aspherical surfaces without rotational symmetry. In Proc. of SPIE Vol. 2653


HWD Examples (Slide 3 of 18)

Mann. Wearable Camera System With Viewfinder Means.
US 6,307,526
Oct. 23, 2001

Geist. Head-mounted virtual display apparatus with near-eye deflecting element in the peripheral field-of-view.
US 6, 771,423
Aug. 3, 2004

HWD Examples (Slide 4 of 18)

Amafuji. Head Mounted Display Device.
US 6,359,602
Sep. 19, 2002

Kuriyama. Image Display Apparatus
US 6,081,304
Jun. 27, 2000

HWD Examples (Slide 5 of 18)

Pekar. Vision enhancing system.
US 4,704,000
Nov. 3, 1987

Togino. Prosm Optical System.
US 5,991,103
Nov. 23, 1999

Furness. Display System for a Head Mounted Viewing Transparency.
US 5,162,828
Nov. 10, 1982

Holakovszky. Stereoscopic video image display appliance wearable on head like spectacles.
US 5,129,716
Jul. 14, 1992

HWD Examples (Slide 7 of 18)

Iba. Image Observation Device.
US 5,384,654
Jan. 24, 1995

US 4,753,514
Jun. 28, 1993

Fig. 1

Fig. 2

Fig. 4

HWD Examples (Slide 8 of 18)

US 5,576,887
Nov. 19, 1996

Lippert. Visor Display with Fiber Optic Faceplate Correction.
US 5,309,169
May 3, 1994

HWD Examples (Slide 9 of 18)


Kasai. A Forgettable Near-Eye Display. ISWC 2000

HWD Examples (Slide 10 of 18)

Bosserman. Toric reflector display.
US 4,026,641
May 31, 1977

Nagaoka. Light weight head mounted image display device.
US 6,697,200
Feb. 24, 2004

HWD Examples (Slide 11 of 18)

Takeyama. Observation optical system.
US 6,710,902
Mar. 23, 2004

Song. Wearable display system.
US 6,882,479
Apr. 19, 2005

HWD Examples (Slide 12 of 18)

Robinson. Video headset.  
US 5,696,521  
Dec. 9, 1997

Fritz. Head mounted display using mungin mirror combiner.  
US 5,838,490

HWD Examples (Slide 13 of 18)

Chen. Helmet visor display employing reflective, refractive and diffractive optical components
US 5,526,183
Jun. 11, 1996

Chen. Wide spectral bandwidth virtual image display system.
US 5,436,763
Jul. 25, 1995

HWD Examples (Slide 14 of 18)

Chen. Ultra-wide field of view, broad spectral band visor display optical system.
US 5,499,139
Mar. 12, 1996

Takeyama. Image display apparatus.
US 6,342,871
Jan. 29, 2002

HWD Examples (Slide 15 of 18)

Togino. Visual display apparatus
US 5,436,765
Jul. 25, 1995

Becker. Head Mounted Display for Minian Video Display System.
US 5,003,300
Mar. 26, 1991

Erfle. Ocular.
US 1,478,704
Dec. 25, 1923

HWD Examples (Slide 16 of 18)
Waveguide with Cascaded Mirror-Array (Lumus)

Y. Amitai, SID Symposium Digest of Technical Papers, 2005
HWD Examples (Slide 17 of 18)
Holographic Planar Waveguide (Sony)

HWD Examples (Slide 18 of 18)
Diffractive Waveguide (Nokia, Vuzix)

T. Levola, Journal of the SID 14/5, 2006
The Origin of Screen-door Effect (SDE)

Ideal white image

Actual White image in VR

Illustration of typical OLED pixel structure

Reducing non-emitting area or increasing open aspect ratio is possible solution for SDE

Non-emitting black space (PDL, Pixel Defining Layer)
Required display specification for “SDE-free”

For 20/20 (foot), 6/6 (metre), 1.0 (decimal) vision acuity

\[ s = 11.6 \text{ um} \] is required for SDE-free
Physical limitation for reducing SDE in OLED

- PDL gap under 12 um is very challenging due to the limitation of evaporation method.
- If small PDL gap is achieved, consumption power and production cost will increase.
OLED with a diffraction grating layer

Micropattern can be specifically designed based on panel information (thickness, refractive index, pixel pitch)

Open aspect ratio of OLED can increase by optical diffusion of pixel light (PDL gap virtually decreases)
Optimization between SDE mitigation and blur is critical to develop solution. Therefore, a quantitative evaluation tool is required.
Quantitative analysis method for SDE and blur

1) SDE estimation (SDE Index)

SDE Index

\[ \text{SDE Index} = \frac{\sum \text{High order spatial frequency power (SDE)}}{\text{Zero order spatial frequency power (Data)}} \]

(By 2D Fourier Transform)

2) Blur estimation

Data (low spatial frequency)
SDE (high spatial frequency)

Bare OLED screen showing SDE

Slope at the edge between black and white
SDE analysis by 2D Fourier transform

**Image space**

- Original Image
- Ideal full white
- Bare OLED
- X45 full white

**Frequency space**

- Magnitude spectrum
- SDE Index = 0
- SDE Index = 30

**2D FFT**

\[ F(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) e^{j2\pi(ux+uy)} dx dy \]

**SDE Index**

\[ \text{SDE Index} = \frac{\sum \text{High order spatial frequency power (SDE )}}{\text{Zero order spatial frequency power (Data)}} \]
Evaluation of SDE mitigation

- SDE mitigation can be visually and quantitatively analyzed by 2D FFT.
- It reveals that adding a diffraction grating layer into OLED display is effective for reducing SDE in VR.
Estimation of blur

Sharpness index

\[ \text{Sharpness index} = \frac{\Delta \text{Brightness}}{\Delta \text{Pixels}} \]