Eye Tracking For The Future: The Eyes Have It

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Outline

Eye Tracking Applications

• Head Mounted Displays (HMDs) (Wearable)
• Remote Eye Tracking
• Eye Tracking User Cases: Vergence; Foveated Rendering. Assistive Technology

Eye Movement and Tracking Methods

• The Eye
• Eye tracking Methods
• Camera Sensors and Technology Suppliers

User Interfaces

• Dwell, Blink
• Saccades
• Smooth pursuit
Head Mounted Displays (HMDs) are Incomplete Without...
HMDs Incomplete Without Eye Interaction

Eye-Tracking & Control in HMDs:

- Navigation
- Activation
- Reading
- Paging
- Searching
- Zooming
- Panning
- Game Interaction
- Multimodal Control
- AR Control
- VR Control
Remote Eye Tracking

Computer monitors, TVs, cell phones

Sample uses:

• Assistive Technology – For people who can only move their eyes

• Driver alertness – Safety for drivers

• Cell phone screen scrolling

Remote eye tracking algorithms require: localizing heads and eyes; larger eye/head box (where we must track the eyes); camera with larger field of view and higher pixel count.
Schematic View Of Eye

- Cornea/lens form image on retina
- High resolution region of retina is called ‘fovea’ ~ few degrees of gaze view in diameter
Eye Features

Prominent eye features

Specular reflections from cornea

Upper Eyelid

Iris

Limbus

Sclera

Pupil

Lower Eyelid

Eyelash shadows
Eye Tracking History

Goal of eye tracking: measure where user is gazing – where is the ‘fovea’ looking

- First Eye tracking in 1800s by observation
- Corneal reflection photos 1d vs. time
- Mechanical eye tracking contact lens with pointers
- Oculography - monitor electric potential in eyeballs
  - can work with closed eyes
- Camera based eye tracking
- Collimated light based eye tracking
Eye Tracking Methods

Main Observables

• Purkinje Images (reflections from various eye surfaces)
• Dark/Bright Pupil
• Glints (1’st Purkinje reflection)

Non-Camera based methods

• Mounting coils on eye or contact lens
• Oculography - measuring electric potentials

Algorithmic Approaches

• Pupil Center – Cornea Center – Example Geometric Approach
• Feature Based – Example Deep Learning Approach
Eye Tracking Methods (Cont)

- Purkinje Images: Reflections from eye surfaces
  - 1’st - Anterior Cornea
  - 2’nd - Posterior Cornea
  - 3’rd - Anterior lens
  - 4’th - Posterior lens
Eye Tracking Methods (Cont)

- Bright/Dark Pupil
  - Closely aligned light source and camera
  - Illuminates retina when light source on
  - Localizes pupil
  - Alternating illumination

Bright pupil in IR - similar to Red eye in visible – camera aligned light source on

Dark pupil in IR
Camera aligned light source off
With visible glint
Eye Tracking Methods (Cont)

Glints - 1’st Purkinje reflection

Basis for pupil center – cornea center algorithms

3 tracked glints

Large pupil, glints, secondary purkinje reflections
Pupil Center Cornea Center

Algorithm basics:
Find two points in 3D space on the eye in camera co-ordinates
Project a vector from the 2 points to where it intersects with the display in camera co-ordinates

Point 1: 3D Cornea Center
• Find glints on cornea
• Solve correspondence for which glint is from which IR-LED
• Project rays from the known location in camera co-ordinates of the LEDs. Glint reflections are equal angle from the incident ray, the normal ray passes through the center of a spherical cornea.
• Intersect the rays to estimate cornea center

Point 2: 3D Pupil center
• Find point in the pupil
• Find edges of pupil
• Fit ellipse or rotated circle to points with Ransac. Avoid eyelids and eye lashes
• Correct for corneal distortion
Approximate Error Tolerance

Consider one of the points as fixed, say the cornea center. CC

Perturb the second point, pupil center, PC, transversely by a small amount and measure the gaze error.

What perturbation, \(dx\), leads to a 0.1 degree angular error?

\[ h \approx 4.2 \text{ mm (cornea center to pupil center)} \]

For a \(d\Theta\) of 0.1 degrees, \(dx\), the measurement error in pupil center is:

\[ dx \approx h \times d\Theta \text{ radians} \]

\[ dx \approx 0.0042 \times 0.1/180 \times \pi = 7 \times 10^{-6} \text{ m or 7 \mu m} \]
System error sources

• Camera lens distortions/intrinsics – errors in all measured quantities
• LED pose – introduces error in cornea center
• Display pose – introduces gaze error
• Glint localization – introduces cornea center error
• Corneal distortion correction for pupil edge – pupil center error
• Pupil ellipse fitting errors – pupil center location
• Spherical cornea assumption - Cornea center location
• Camera-Camera pose - binocular gaze errors
Neural Network – Deep Learning Approaches

Sample Neural Network Architecture for Remote Eye Tracking

Training data from 1471 subjects
Accuracy reported as ~1.04 cm on cell phone screen and ~1.69 on tablet screens
(Estimate 1.5 degrees average gaze error)

Note from paper:
Data preparation: First, from the 2,445,504 frames in GazeCapture, we select 1,490,959 frames that have both face and eye detections

Eye Tracking for Everyone K. Krafka*, A. Khosla*, P. Kellnhofer, H. Kannan, S. Bhandarkar, W. Matusik and A. Torralba
IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2016
Some Challenging Situations...

Unusual Pupil - Rare

Partially Occluded Pupil and eyelash blocking pupil (both very common)

Very occluded pupil
Eye Movement

Eye is fastest moving part of human body, up to 900 degrees/second for large saccades. Constrains measurement system

- At 30 Hz camera frame rate, eye moves up to 30 degrees between measurements
- 1 msec camera integration time, eye moves ~0.9 degrees, blurring the images

Eye constantly moving, typical ~0.5 degrees

- Microsaccades, drift and tremors
  
  Microsaccade shown in red. Drift and tremors in black.
  
  Typical amplitude ~ 0.5 degrees
Blinks

- Blinks - noise source for eye tracking
  - Inadvertent eyeball movement during pre/post blink
  - Partial pupil occulsions
- Blinks - interesting signal correlated with drowsiness
- Typical blink periods ~few hundred milliseconds, increasing with drowsiness
- Eye moves in socket during blink. Eye is blind around blink

The duration of eyelid movements during blinks: changes with drowsiness
## Camera Requirements for AR/VR Eye Interaction

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutter</td>
<td>Global Shutter</td>
<td>Short exposure times. Short illumination time for power saving, eye safety, avoid motion blur</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>100-200HZ (FR); 30+ (UI); 1+ (IPD, user recognition)</td>
<td>Most devices will have mixture of camera modes based on use cases</td>
</tr>
<tr>
<td>Eye spatial resolution</td>
<td>~0.05-0.1 mm/pixel</td>
<td>Resolve eye structures, eye tracking accuracy</td>
</tr>
<tr>
<td>Pixels</td>
<td>~QVGA</td>
<td>Depends on field of view of lens, HMD IPD adjustment, camera mounting locations</td>
</tr>
<tr>
<td>Illumination Wavelength</td>
<td>&gt;840 nm</td>
<td>Illuminator not visible to users</td>
</tr>
</tbody>
</table>
## Computational Requirements for AR/VR Eye Interaction

<table>
<thead>
<tr>
<th>Specification</th>
<th>Geometric Algorithm</th>
<th>Deep Learning Algorithms</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIPs/Image</td>
<td>30 MIPS/Image</td>
<td>5000 MIPS/Image</td>
<td>Sample values from two different systems.</td>
</tr>
<tr>
<td>Memory</td>
<td>Megabytes</td>
<td>~Gigabyte</td>
<td></td>
</tr>
<tr>
<td>Power use</td>
<td>GOPs ARM based embedded system</td>
<td>TOPs Neural Network accelerator</td>
<td>Geometric algorithms demonstrated on single core A9 processor. Neural Network algorithms demonstrated on Nvidia Jetson GPU. Other neural network algorithms demonstrated on cell phones</td>
</tr>
</tbody>
</table>
Technology Suppliers

Eye Tracking: 7Invensun, AdHawk, Argus, Ganzin, Tobii, Xperi, ... others

Remote tracking Systems: Eyetech, Tobii, Eyeware, ... others

HMDs: Microsoft, MagicLeap, HTC, ... others
Use Cases: Vergence-Accommodation In HMDs

- Vergence-Accommodation display disparity can cause user problems, including headaches, in wearable display systems

- Vergence can be measured by binocular gaze tracking systems and used to refocus display light from the point of gaze

**Accommodation** is the adjustment of the optics of the eye to keep an object in focus on the retina as its distance from the eye varies

**Vergence** is the simultaneous movement of both eyes in opposite directions to obtain or maintain single binocular vision
Use Case: Foveated Rendering (FR)

Rendered image is combination of high resolution rendering at gaze point (red) and lower resolution further from foveal region of eye

Save power and MIPS by rendering gaze target/foveal region at high resolution

Some display controllers will require foveated transport, sending ‘compressed’ FR data to the display panels

Gaze measurement selects where to render image at highest quality. Low latency required to save rendering processing – smallest high resolution regions

From Microsoft
The eye is not a mouse, touch screen, hand or keyboard – it is an eye

- For control of a user interface – let the eyes do what the eye do
- Avoid cursors, dwell, blink
  - (Without a cursor, how do I know where I’m looking ... you are looking there!)
- Use subtle UI elements
- Take advantage of saccadic blindness.

Eyes are the fastest moving part of a human
User Interfaces

• Pointing/Selecting
• Activating
• Saccades
• Smooth pursuit
User Interfaces

Selection – Where you are looking

Main Reveal, with timeout to guide eye and avoid inadvertent activations

Activation – use memory guided saccades to activate

Main Reveal – shows faint home, back and menu items. Memory guided saccades activate them

Excellent! Look from the eye (upper-right) to the Home icon (lower-right) to go home.
User Interfaces

• Augmented Reality User Interfaces
  • Avoid inadvertent activations by adding friction to irreversible actions
  • Sufficient contrast for visibility in real world environment

• Virtual Reality User Interfaces
  • Maximum Saccade length 15-20 degrees – larger is tiring, design likely requires dynamic placement of UI elements
  • Consider taking advantage of head movement in combination with eye movement
  • Consider using secondary activation device – a clicker for example
Conclusion

• Accurate robust eye tracking requires detailed system design and error/tolerance analysis

• Applications such as IPD measurement, foveated rendering appearing in shipping products

• Eyes can be used to control a user interface

Eye Tracking is NOT completely solved – room for new solutions!

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Advisor to Lemnis Technologies: solutions for vergence accommodation conflict in AR and VR Headsets

Advisor to Kura Technologies: Building the next generation AR HMD.

Contact: Peter Milford pmilford@parallel-rules.com
The duration of eyelid movements during blinks: changes with drowsiness
Tucker, A., & Johns, M. W.

Microsoft Foveated Rendering Paper
NVIDIA Foveated Rendering Paper

Papers on Eye tracking:
Eye tracking, general (paywall)
Remote Eyetracking, geometric
Cell Phone based deep learning

Vergence/Accommodation solutions