I SEE WHAT YOU SEE: POINT OF GAZE ESTIMATION FROM CORNEAL IMAGES

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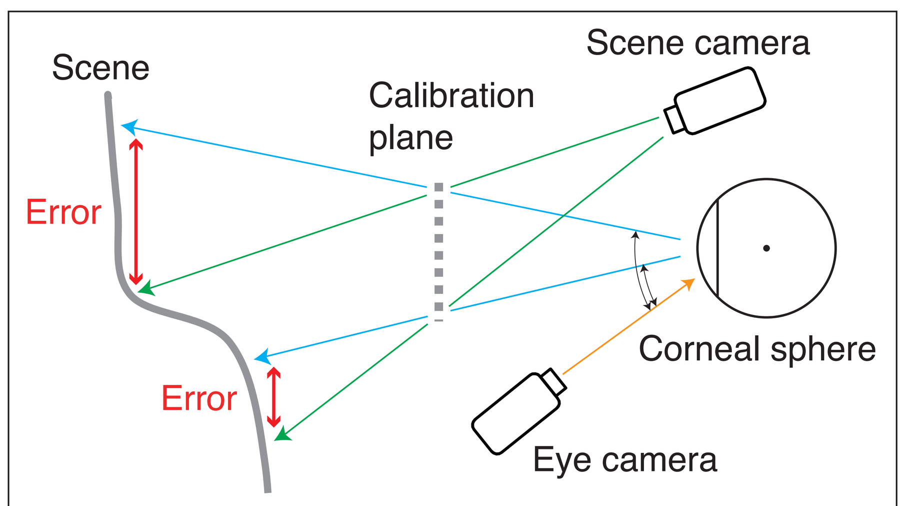
OVERVIEW

(A) PROBLEM

Eye-gaze tracking (EGT) has applications in various fields, such as HCI, psychology, medicine, engineering and marketing [1].

However, state-of-the-art techniques still require a calibration of the relation between eye and scene to obtain the Point of Gaze (PoG):



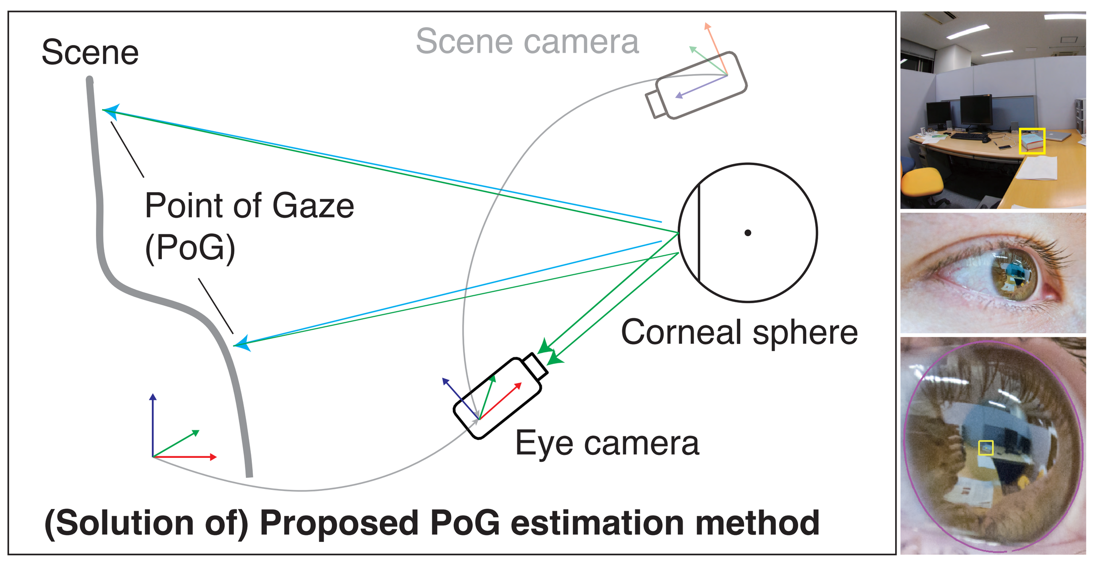
(Problems of) Existing PoG estimation methods

This relates to a number of **limitations**:
1. It requires expert knowledge and efforts.
2. It restricts to planar scenes, and
   does not allow for dynamic scenes and flexible setups.
3. Changes lead to accumulating errors, especially
   ▪ a drift error, when components change their relative pose,
   ▪ a parallax error when the depth of the scene varies.
4. It relies on complex machinery and controlled environments.
5. It obtains the PoG, but no information about peripheral vision.

(B) PROPOSED SOLUTION

This paper introduces a **novel concept for EGT that overcomes these limitations** using corneal imaging.

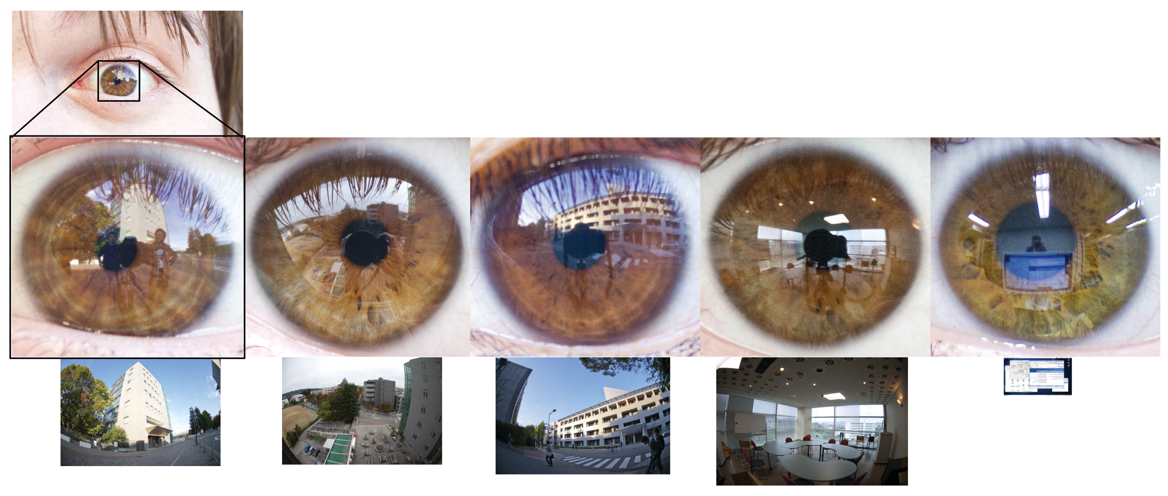
It is shown how to extract scene information and determine the point of gaze (PoG) directly in an eye image.



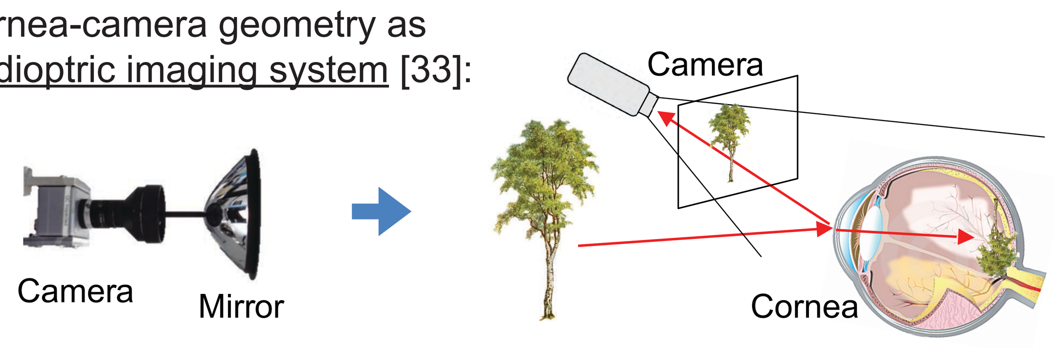
(Solution of) Proposed PoG estimation method

Contribution:
1. Calibration-free PoG estimation in an eye reflection image
2. Concept and analytic solution for Gaze Reflection Point (GRP)

Corneal imaging [7,8]:
A face image captures information about observer and environment as the cornea reflects a wide-angle view of the environment:



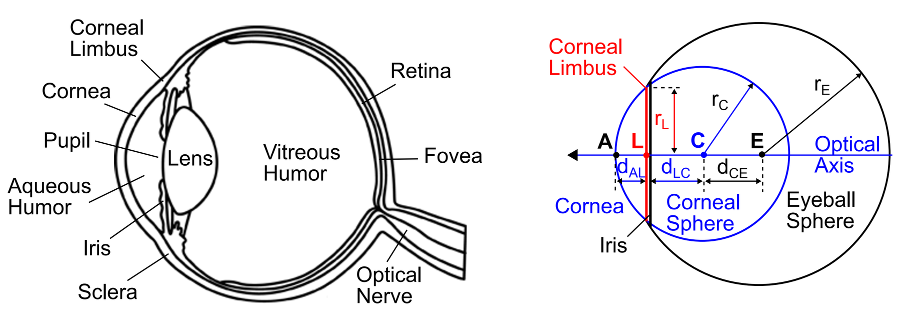
This information can be extracted from an image by modeling the cornea-camera geometry as a catadioptric imaging system [33]:



Relation to our ECCV 2012 paper [14]
In [14] we describe a system to actively illuminate a scene by coded IR-light for robust matching of eye and scene images at the PoG. This paper describes a more general PoG estimation framework that does not require complex hardware and controlled environments.

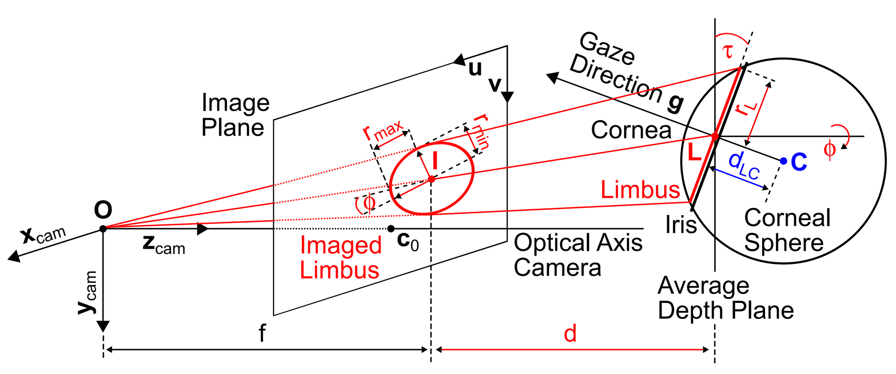
METHOD

(A) GEOMETRIC EYE MODEL

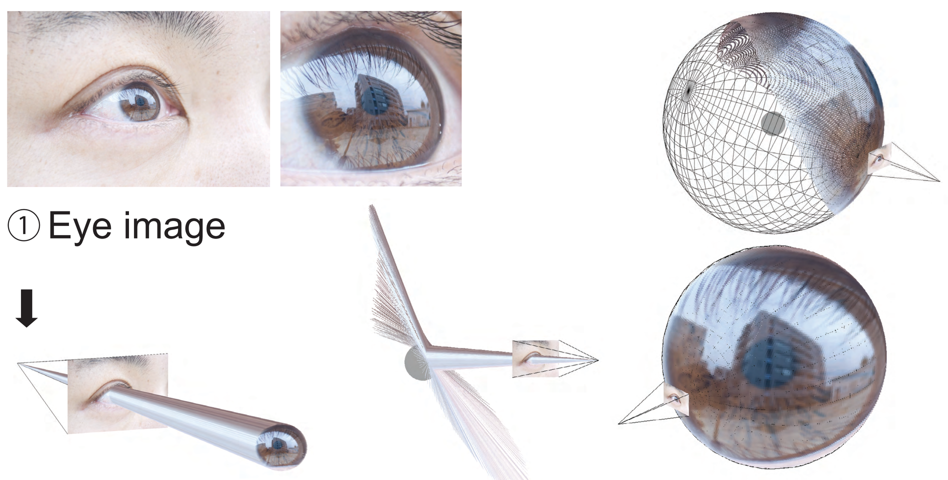


Cross section of eyeball   Spherical eye model

(B) EYE POSE AND GAZE DIRECTION



(D) CORNEAL REFLECTION MODEL

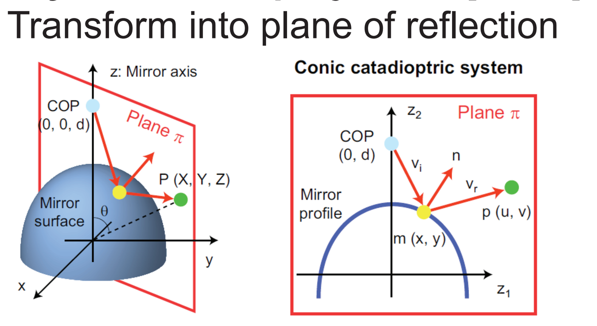


① Eye image
② Back-projection ➡ ③ Reflection ➡ ④ Light map

(C) GAZE REFLECTION POINT (GRP)

GRP: Point, where light from the PoG reflects at the corneal surface

Analytic forward projection [13,32]:
1. Transform into plane of reflection



2. Solution constraints

Mirror equation: $x = \pm\sqrt{C - By - Ay^2}$

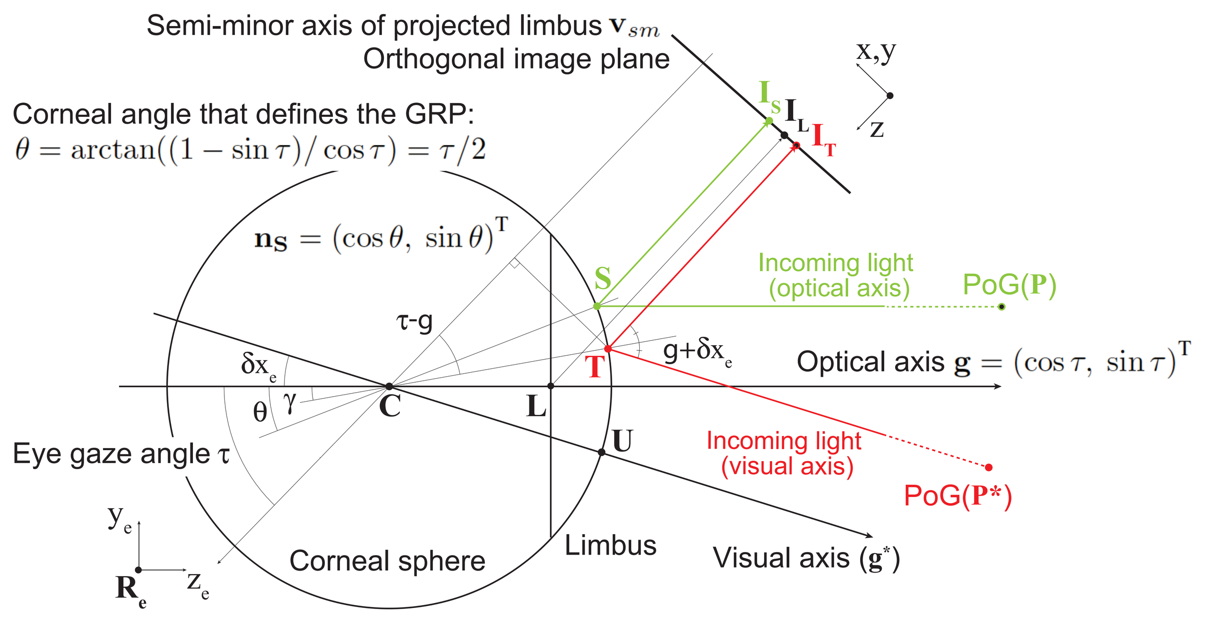
Law of reflection: $\mathbf{v}_r = \mathbf{v}_i - 2\mathbf{n}(\mathbf{n}^T\mathbf{v}_i)/(\mathbf{n}^T\mathbf{n})$.

$$\mathbf{n} = \begin{bmatrix} x \\ B/2 + Ay \end{bmatrix}, \quad \mathbf{v}_i = \begin{bmatrix} x \\ y - d \end{bmatrix}$$

Intersect P: $\mathbf{v}_r \times (\mathbf{p} - \mathbf{m}) = 0$

⇨ 4th-order equation in one unknown

(1) Forward projection at spherical mirror with unknown scene distance
▪ Plane of reflection intersects semi-minor axis of projected limbus
▪ Distant scene: lightray parallel to gaze direction reflects at GRP into camera



Distance between limbus center and GRP in image plane: $|\mathbf{I_S} - \mathbf{I_L}| = r_C \sin\theta - d_{\mathbf{LC}} \sin\tau$
Image location of GRP: $\mathbf{i_S} = \mathbf{i_L} + s \cdot \mathbf{v}_{sm} |\mathbf{I_S} - \mathbf{I_L}|$ $s = r_{\max}/r_L$

(2) One point calibration of individual offset between optical and visual axis
▪ Gaze at calibration point in scene and calculate its GRP, S
▪ Calibration point reflects at calibration reflection point (CRP), T
▪ Use angular difference between the two axes $(\delta x,\ \delta y)$ to compensate the offset

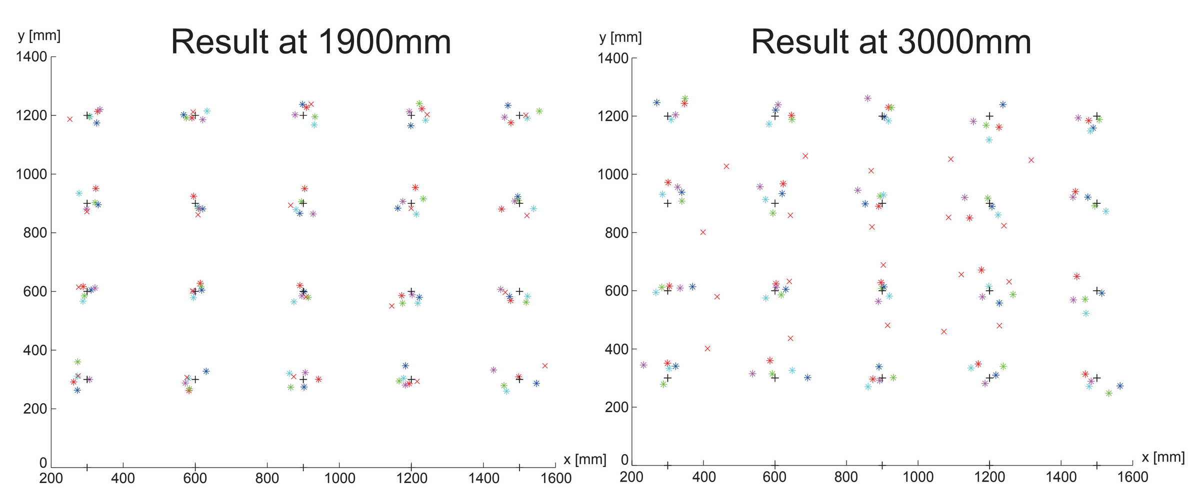
Scene image | Eye image | 180° Spherical | 140° 48° Perspective — Re-projected corneal image

EXPERIMENTS

(A) QUANTITATIVE COMPARISON WITH MAPPING-BASED PCCR METHOD [14]

TABLE II
MEAN VISUAL AXIS ESTIMATION ERROR [DEG].

	Condition 1 (depth = 1900 mm)		Condition 2 (depth = 3000 mm)	
	This method	PCCR	This method	PCCR
Subject 1	0.960	0.973	0.909	3.084
Subject 2	0.913	1.032	0.642	4.350
Subject 3	0.916	0.963	0.756	3.560
Subject 4	0.947	0.890	0.759	3.951
Subject 5	0.761	1.121	0.914	4.240
Mean	**0.899**	0.996	**0.796**	3.837



Error measures:
Proposed method: angular error between GT marker and gaze direction in corneal image → distance error
PCCR: angular error ← distance error between GT marker and PoG from calibrated mapping

Results:
▪ The performance of PCCR decreases when the depth changes (condition 2) due to a parallax error.
▪ The proposed approach performs stably, with an error <1° under varying depth conditions.
▪ The error scales with distance between eye and scene.
▪ The error scales with gaze angle from the central direction (due to previous and errors in eye pose estimation).

(B) QUALITATIVE EVALUATION

▪ Although, the cornea is not a perfect mirror and suffers from several issues, these decrease towards the apex. Thus, the re-projected images from the central area, including the GRP, show rich scene details.
▪ The method works well under challenging bright outdoor lighting conditions. In fact, this even increases the quality of iris contour tracking and obtained corneal images.

CONCLUSION

The paper introduced the first EGT approach that estimates the PoG w.r.t. the reflected scene in an eye image. The two main contributions comprise
(1) the concept of direct PoG estimation, and
(2) an analytic solution for the GRP, including the individual offset between optical and visual axis.

The approach overcomes two major limitations of existing methods, namely,
(1) a calibration of the relationship between eye camera and scene, and
(2) a parallax error that occurs under varying scene depth.

Advantages allow novel applications and scenarios, including
(1) EGT with infants and disabled,
(2) wearable EGT with ubiq. cameras / AR-HMDs (Google Glass [15]), and
(3) remote EGT, surveillance, forensics.

Corneal Imaging Code for MATLAB
http://goo.gl/VdNYKI

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