Wide-range High-precision Eye-tracking based on Purkinje Reflections

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ABSTRACT

Humans continually move their eyes to explore the visual world. Precisely measuring eye movements is, therefore, crucial for both understanding human vision and paving the way for the next generation of augmented and virtual reality devices. Imaging Purkinje reflections enables high-resolution eye-tracking over a limited range. Here we present an optical architecture that enables extension of the tracking range while maintaining 1 arcmin resolution.

1. INTRODUCTION

The human eye is always in motion. Rapid gaze shifts (saccades) occur several times per second, and smaller eye movements occur even during the inter-saccadic periods of fixation [1]. As a result, reliably measuring eye movements and determining the subject's direction of gaze is key for both fundamental vision science and optical technologies that pair with the human eye, especially augmented and virtual reality devices [2].

A particularly robust method for measuring eye movements is the dual-Purkinje eye-tracker that relies on partial (Purkinje) reflections from the front surface of the cornea (P1) and the back surface of the lens (P4) [3, 4]. When exposed to a collimated beam, the human eye forms images of P1 and P4 on approximately the same plane due to its optical geometry. The distance between the two reflections is linearly dependent on the angle of eye rotation. This relationship was utilized to develop an analogue dual-Purkinje eye-tracker with the ability to detect sub-arcminute eye rotations [3]. Recent advances in digital imaging have enabled the development of a more compact and much easier-to-use digital dual-Purkinje (dDPI) eye-tracker [4]. However, the range over which this system operates at a high resolution is limited to approximately ±7.5 degrees. Here we present a recently conceived optical configuration that operates reliably over a 40-degree tracking range, featuring a modular design that could be optimized for different tracking ranges.

2. METHODS

A dual-Purkinje eye-tracker was designed using two tilted illuminators and a relay lens imaging the Purkinje image plane onto a high-speed detector.

Two 850-nm LED sources are collimated using two identical lenses with 36-mm focal lengths to ensure pupil matching under 20 degrees of eye rotation in the horizontal direction. The collimated beams are then directed to the eye using a dichroic mirror, incident on the eye at symmetric angles. Optical analysis in CODEV suggests that the angle of the illumination beam plays a key role in determining the trackable range of dual-Purkinje eye-trackers. Each illuminator creates a tracking footprint that is biased in the direction of illuminator placement. To cover a trackable range of 40 degrees in the horizontal direction, two illuminators are offset horizontally. This creates two tracking regions: a central region where two P1 and two P4 reflections are visible and eye tracking can be performed using two P1/P4 pairs, and the edge regions where only one P4 is visible, and tracking is done analyzing a single P1/P4 pair following the traditional dual-Purkinje tracking principle.

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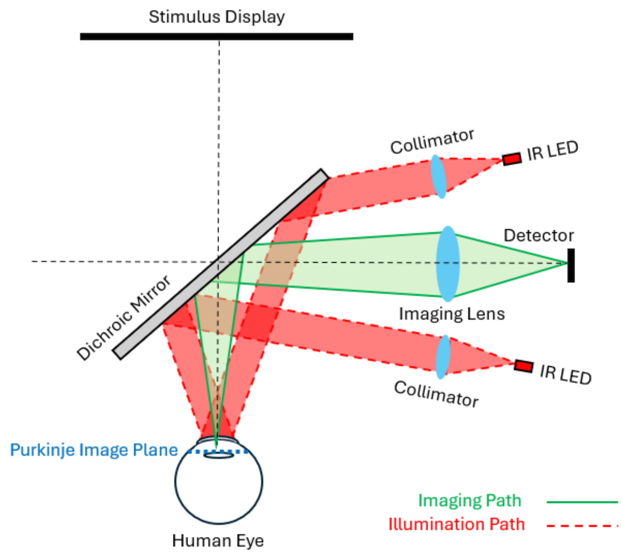

Fig. 1. Optical layout of the eye-tracking system showing the human eye observing a stimulus on a display and the eye-tracker placed to the side utilizing the reflective properties of the dichroic mirror in the IR.

The imaging arm of the system consists of a relay lens with an IR filter that images the Purkinje reflections onto a detector with a magnification of 1.25. The magnification was selected to ensure sufficient change in separation between the reflections on the detector plane under 1 arcmin of eye rotation.

3. RESULTS

The system was tested with both an artificial eye and the human eye. The artificial eye is a model designed to replicate the size, shape and optical properties of the real eye, containing an external fluid-filled transparent region that represents the cornea, and a lens that mimics the crystalline lens of the human eye. The artificial eye was rotated manually, and both P1/P4 pairs remained visible for the 40-degree range. For testing the human eye, subjects were asked to fixate on points placed at different visual field angles, and the P1/P4 images were acquired for different fixation angles. As expected, both P1/P4 pairs were visible when the subjects were fixating in the central region, and one of the P4 reflections would disappear as the subjects would look to the sides. With at least one P1/P4 pair being visible across the full range, dual-Purkinje tracking is now possible across a significantly wider range.

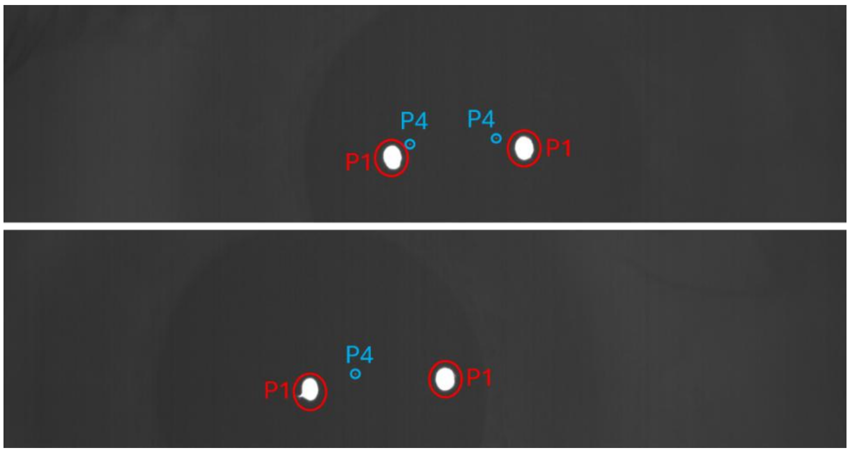

Fig. 2. Images acquired from the eye-tracker. (Top), Both P1/P4 pairs are visible when the subject looks straight ahead. (Bottom), One of the P4 reflections is no longer visible when the subject looks eccentrically (here 16 deg to the left), but tracking can be done using the remaining visible pair.

4. CONCLUSION

The optical architecture for the dual-Purkinje eye-tracker we developed greatly expands the trackable range while maintaining the resolution necessary to perform high-precision eye-tracking.

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