

High-Resolution Eye Tracking Using Scanning Laser Ophthalmoscopy

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ABSTRACT

Current eye-tracking techniques rely primarily on video-based tracking of components of the anterior surfaces of the eye. However, these trackers have several limitations. Their limited resolution precludes study of small fixational eye motion. Furthermore, many of these trackers rely on calibration procedures that do not offer a way to validate their eye motion traces. By comparison, retinal-image-based trackers can track the motion of the retinal image directly, at frequencies greater than 1kHz and with subarcminute accuracy. The retinal image provides a way to validate the eye position at any point in time, offering an unambiguous record of eye motion as a reference for the eye trace. The benefits of using scanning retinal imaging systems as eye trackers, however, comes at the price of different problems that are not present in video-based systems, and need to be solved to obtain robust eye traces. The current abstract provides an overview of retinal-image-based eye tracking methods, provides preliminary eye-tracking results from a tracking scanning-laser ophthalmoscope (TSLO), and proposes a new binocular line-scanning eye-tracking system.

CCS CONCEPTS

• Human-centered computing → Human computer interaction (HCI); Systems and tools for interaction design; • Applied computing → Psychology.

KEYWORDS

Scanning Laser Ophthalmoscopy, Binocular Eye Tracking, Fixational Eye Motion

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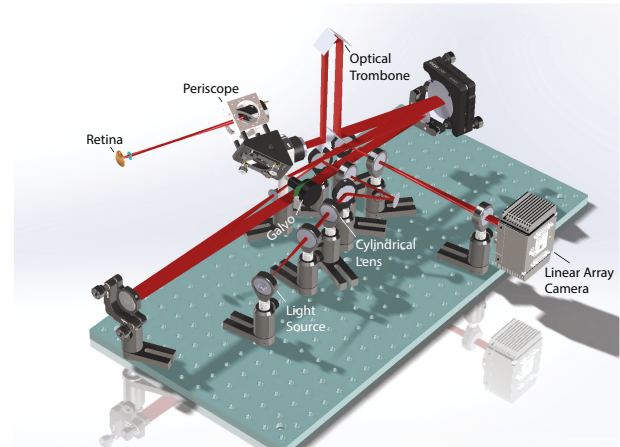


Figure 1: Schematic of one side of binocular line scanning ophthalmoscope. The beam from a light source is passed through a cylindrical lens to form a horizontal line, which is onto the subject's retina. An optical trombone enables refractive correction and a galvo scanner sweeps the line across the retina. The light scattered from the subject's retina is descanned through the optic path and imaged onto linear array camera, line by line, to create a movie of the subject's retina. As is evident in the design, there is ample eye relief, allowing for the integration of additional devices such as video-based eye trackers.

1 RESEARCH OBJECTIVES

There is a need to build retinal-image-based eye tracking systems that (i) generate eye motion traces that are free of artifacts, (ii) that can achieve optimal accuracy but still track over a large field, (iii) that can track both eyes simultaneously, (iv) that can measure torsional eye movements, and (v) that have sufficient eye relief (space between the last optical component and the eye) to facilitate simultaneous measurement and comparison with more conventional video eye tracking systems. Fig. 1 shows the proposed apparatus for one eye.

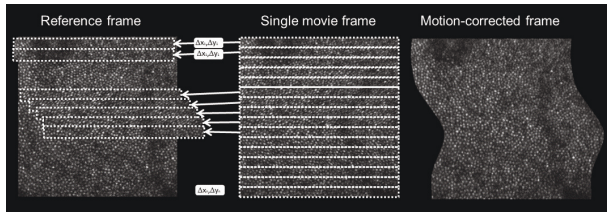


Figure 2: Eye tracking is achieved by taking a single reference frame (left panel). Every subsequent frame is distorted by the eye movements. This single movie frame has a shear distortion caused by a microsaccade. To remove these distortions, individual frames are cross-correlated, strip by strip, with the reference frame. The X and Y strip displacements required to align the strips are used to render a motion-corrected frame and provide a record of the eye trace.

2 HYPOTHESIS AND PROBLEM STATEMENT

The specific class of eye trackers described here are retinal-scanning systems. One such system, the TSLO, scans light across the retina in a raster pattern to obtain high-resolution images of retinal structure. Because the top of each frame occurs earlier in time than the bottom, any eye movement that occurs during that time gives rise to unique distortions in each frame. These distortions allow recovery of eye motion at a greater temporal resolution than the frame rate. The process involves breaking each movie frame into strips, which are individually cross-correlated against a reference frame to acquire ΔX and ΔY offsets. (Fig. 2, left panel)

It is possible to extract eye traces at high frequencies with this technique [Sheehy et al. 2012]. In systems that employ adaptive optics, eye traces are accurate to within less than a minute of arc [Stevenson et al. 2010]. The process also generates a stabilized version of the movie where the frame itself will move instead of the eye, so that features on the retina are stationary. This stabilized movie can validate the accuracy of the trace (Fig. 2, right panel).

Scanning retinal-based eye-tracking systems, however, face several unique problems that must be accounted for.

Dynamic Range. The size of the raster on the retina only subtends a few degrees, which limits the effective range of the tracker. If the subject makes a saccade that is much larger than the raster size, then the ability for the cross-correlation to realign those strips onto the reference will deteriorate because the TSLO is now imaging a different part of the retina. Consequently, the TSLO is only able to measure eye motion over a relatively small range.

Artifacts from Reference Frame Distortion and Torsion. Any distortions in the reference frame present a periodic artifact in the eye trace at the frame rate. Additionally, if the eye undergoes torsion, subsequent frames of the movie will be rotated. The cross-correlation technique currently does not account for torsion. Instead this technique attributes torsion to a horizontal shear. The strips corresponding to the top of the frame are shifted in one direction and the strips corresponding to the bottom are shifted the opposite direction. This introduces a sawtooth artifact in the trace, the amplitude and direction of which is directly tied to torsion.

Eye Relief. Retinal imaging systems typically have very little eye relief (the space between the system's final optical component and the eye). To expand the scope of applications to include calibration of other types of eye trackers, maximizing the eye relief is essential.

Binocular Operation. With one exception [Stevenson et al. 2016], retinal-image-based systems typically lack the capability to track both eyes simultaneously, so important information about binocular eye motion is not recorded.

3 APPROACH AND METHODS

The TSLO has many issues that must be addressed before it can be used as a high-resolution eye tracker, but many of these problems are tractable. In order to extend the effective field of view, multiple images can be combined to obtain a wide-field, high resolution image of the retina which can be used as the reference [Chen et al. 2016]. Such an approach would allow tracking the subject's gaze well beyond the limit imposed by the raster size. Furthermore, by combining multiple small TSLO images, there is no loss of resolution, so the cross-correlation will function well. Eye-trace artifacts arising from distortions in the reference image or torsion present a greater challenge. Several approaches to mitigate reference frame distortions are currently being applied [Azimipour et al. 2018; Bedgood and Metha 2017; Vogel et al. 2006]. Torsion, however, is a much trickier problem. Because torsion is a relatively slow movement [Van Rijn et al. 1994], one can measure it by rotating entire frames, but the inter-frame distortions often preclude a reliable full-frame alignment. The ideal approach to measure torsion, therefore, is to increase the frame rate of the system, which is described below in *Future Work*. With increasing frame rate, inter-frame distortion becomes smaller and less problematic. Finally, the inability of the TSLO to image both eyes simultaneously can be solved by creating two separate apparatuses, one for each eye, and temporally syncing the hardware components.

4 PRELIMINARY RESULTS

To establish a proof of principle, a TSLO has been used to address some of the limitations described above. To overcome the inability of the TSLO to track over a wide field, a montage of images was created using the techniques outlined in the previous section. The montage was smoothed along the overlapping frame edges to reduce registration artifacts. By using the montage as an oversized reference, a movie of the retina of a subject engaged in a free-viewing task was stabilized against the montage to obtain eye traces. A video animation can be seen at this link: https://www.dropbox.com/s/bxaxr73sdb2dl2h/RESULT_VIDEO_59.mp4?dl=0. Thus far the eye traces have only been tracked frame by frame and have not yet been divided into strips.

5 FUTURE WORK

The preliminary work with the TSLO will serve to facilitate the development of the processing pipeline, but a new system is needed to achieve our research objectives. The new system will be a binocular line-scanning laser ophthalmoscope. The line scan has the advantage of increasing the frame rate by up to 10X. The higher frame rate enables a pyramidal approach to generate the eye-motion traces. Full frames will be aligned with the reference in order to

obtain rough eye positions before dividing the frames into strips. The device will have ample eye relief, which will allow our system to be used in tandem with most commercial video eye trackers. New developments in the image-processing pipeline are also being made and are being implemented within the Retinal Video Analysis Suite (ReVAS) (<https://github.com/lowvisionresearch/ReVAS>).

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