SCANNING DIFFRACTIVE OPTIC ELEMENTS FOR UNTETHERED EYE-TRACKING MICROSYSTEMS

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ABSTRACT

A microsystem for precise tracking of human eye movements has been developed to meet the stringent requirements of wearable augmented/virtual (A/VR) systems. Eyeglasses retrofitted with the reported microsystem achieve robust tracking with a 120Hz refresh rate and 0.4° RMS noise within a 20mW power budget. The key component in the present system is a compact (650μm x 500μm) scanning diffractive optic element (DOE) that projects and scans a crosshair pattern over a 45° x 45° range.

INTRODUCTION

Eye Tracking Background

The movement of the human eye reveals a wealth of information about an individual's neurological health, ocular health, state-of-mind, and interests [1]. The study of microsaccadic eye movements has provided notable insight into the mechanisms of the oculomotor pathway [2], and may shed light on the pathogenesis of neural disease. Eye-tracking has enabled augmentative alternative communication (AAC) devices for those lacking speech capability and/or motor skills, and is also emerging as a human-computer-interaction (HCI) peripheral that promises to enhance the immersive experience of VR and AR systems.

The most widely used eye trackers today are video-based image processing systems. Such systems are bulky (>1cm³), expensive (>\$100), power-hungry (>100mW), and slow (~60fps) and have therefore not been broadly adopted in mobile or wearable technology. Although medical-grade systems may obtain 500Hz tracking with 0.5° resolution, these systems are massive, may require head stabilization, and often carry price tags that exceed \$50,000 USD. Eye-tracking sensors must be improved significantly to provide seamless human-computer interaction (HCI) with connected devices in a mobile, wearable context.

Of the >50 commercial V/AR headsets, there are none that offer un-tethered eye-tracking at the time of this writing, because of the high power consumption and computational expense of video-based methods. The present work may alleviate these constraints to enable wireless eye-tracking in mobile devices.

Eye Tracking Microsystem Design

The reported eye-tracking system achieves improvements in size, cost, power consumption, bandwidth and precision through the use of a simple design principle (Fig. 1). A low-irradiance (1-10 μW/cm²), infrared (850nm), diverging (at ~50mrad) beam of light is steered by a scanner and reflected from the surface of the cornea at a glancing angle (60° to the normal) onto a photodiode. As the eye rotates, the beam tracks the unique point on the cornea that maximizes the received signal at the photodiode. A noteworthy aspect of the system is that the surface area of the photodiode acts as a spatial filter to remove high frequencies from the far-field pattern projected by the scanner. Large aperture micromirrors with flat surfaces that are ideal for imaging systems [3] are therefore not required. Instead, a small (300μm) Fresnel lens that projects a pattern of high spatial frequencies may be used.

Several improvements to the system reported in [4] have augmented the robustness, speed, resolution, and ease of integration of the present system.

Figure 1: Depiction of eye-tracking system geometry integrated within 3D-printed spectacle frame (inset). In this prototype, the VCSEL, scanner, and photodiode are housed in separate modules.

DEVICE GEOMETRY

The devices incorporate Fresnel zone plates that are mounted on 2DOF scanners (Fig. 2). The scanner design reported previously is isothermal in one axis only; the scanner reported here consists of opposed serpentine actuator pairs. Upon release, the device remains flat due to the symmetrically opposed torques applied by each pair of actuators. To rotate the reflector, the temperature of one actuator is increased, while the opposed actuator's temperature is decreased proportionally. In [4], a square-root operation was performed on the DC voltages applied to a single isothermal pair; the orthogonal axis was non-isothermal.

Figure 2: Fresnel zone plate scanner with 2 degrees of freedom. Symmetrically opposed serpentine actuators are used to achieve angular deflections while suppressing thermal crosstalk.

To control a 2D isothermal device, one may require 4 digital-to-analog converters and a controller that performs the square-root operation. Unfortunately, the cost and power consumption of such an arrangement are prohibitive. The present design may be operated using pulse-width-modulation (PWM), enabling an all-digital drive scheme that linearizes electrothermal actuator trajectories while consuming less power. In addition, 2DOF isothermal actuation suppresses the cross-talk between the orthogonal scan axes that was observed in prior work. The configuration in Figure 3 permits the use of 2 PWM channels to control both axes of the device.

Figure 3: Wiring diagram of PWM drive scheme that requires 1 PWM channel per axis of rotation.

The -3dB bandwidth of the scanners has been increased from 170Hz to 300Hz by reducing the thermal impedance between polysilicon heaters and the bimorph materials. The resonant amplitude has increased by 300% due to improved actuation efficiency at higher frequencies, and also due to a significant reduction in viscous damping caused by the DOE.

TRACKING METHODS

A beam with a ~1mm waist at the surface of the cornea was scanned by the Fresnel reflector. Tracking in the horizontal direction was performed with a fast linear trajectory (120Hz), while a hill-climbing algorithm was used for position sensing in the vertical direction. The signal captured by the photodiode over the course of a single line scan is shown in Figure 4. This data was obtained using a model eye in an enclosure. The top curve was captured with the eye pointing to the left, while the bottom curve corresponds to eye pointing to the right.

Figure 4: Oscilloscope captures of photodiode signal during a line scan. A peak is captured in each direction of the line scan. The delay between the peaks may be used to estimate gaze direction.

With human subjects, the tracking signal was often lost due to eye blinking or rapid vertical movements, so a complete raster scan of the corneal surface was required for recovery.

Improved tracking

The DOE in Figure 4 employs the superposition of an orthogonal pair of cylindrical Fresnel patterns to project a crosshair (Fig. 5). A circular trajectory of the crosshair guarantees that pulses may be captured by the photodiode within every loop; the timing of these pulses correlates to eye position. Edge-triggered measurements offer significant improvements in SNR when compared to voltage measurements that are susceptible to ambient noise and variations in the optical path lengths caused by eye movement. The position noise in prior work was 5° when tracking at 50Hz. The RMS phase noise of measured pulses indicates that flicker noise from ambient fluctuations dominates in unpackaged MEMS devices. Measurements obtained in an enclosure indicate that a packaged device may achieve 0.4° of RMS phase noise while scanning at 120Hz.

Figure 5: 2 degree-of-freedom scanner with a payload that consists of 2 cylindrical lens patterns that are arranged orthogonally to project a crosshair.

A compact scanner module was assembled in order to test the performance of the system integrated into a pair of spectacles (Figure 6). A lensed VCSEL projects a beam onto the DOE surface, which is oriented to scan the surface of the cornea at a glancing angle. The alignment tolerances between the VCSEL and micromirror are significantly more relaxed than the configuration reported in [4], and may therefore be readily assembled by hand. The lens may be removed from the VCSEL at the expense of tighter assembly tolerances. Such an optical arrangement may be achieved using wafer-level bonding techniques.

Figure 6, left: depiction of a crosshair sweeping a circular path over the surface of the cornea – peaks are detected at various points in the path. Right: compact scanner module.

The far-field pattern from the DOE contains high spatial frequencies, as measured with a beam profiler (Fig. 7). These features are filtered by the large aperture of the photodetector.

The static and resonant deflections of the crosshair pattern were measured with an IR camera. In [4], the resonant deflection was approximately the same amplitude as the DC deflection, in part because of viscous damping of the large mirror plate with relatively small etch holes. The DOE scanner experiences less drag and therefore achieves a resonant displacement that is 3x greater than the mirror's. In addition, the polysilicon heater placement in the DOE device provides greater efficiency at higher frequencies, due to a lowered thermal time constant.

Figure 6 (a): beam profile of crosshair pattern projected by DOE. (b) static deflection of crosshair pattern captured with an IR camera. (c) resonant deflection of crosshair pattern captured with an IR camera.

A calibration algorithm was developed to map measured eye-position values onto a 2D coordinate system (i.e. a computer screen). Users were instructed to direct their gaze at several points on the screen, and a multivariate regression was used to extract polynomials to correct all subsequent measurements (Fig.4).

SUMMARY

Conventional methods of eye-tracking have enjoyed a wide range of applications including augmentative alternative communication, video game interaction, and clinical research; however, several barriers may prevent the adoption of video-based eye-trackers by the emerging wearable electronics enterprise. A microsystem based on scanning DOEs has been developed to achieve high-speed, low-power, low-cost, accurate tracking of eye movements.

Figure 7 (a): data from a calibration procedure in which the user is instructed to look at several points on the screen. (b) A multivariate regression is performed on the inner 9 points, resulting in the corrected values of the outer 9 points in red.

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