# VR Eye-Tracking using Deflectometry

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**Abstract:** We present a novel approach for accurate eye tracking as required, e.g., in VR/AR/MR headsets. Our method exploits the retrieved surface normals and dense 3D features extracted from deflectometry measurements to estimate the gazing direction. © 2021 The Author(s)

## 1. Introduction

Although the task has been studied for several decades, a robust solution to accurate and fast eye tracking remains an unsolved problem. With the advent of Virtual, Augmented, or Mixed Reality (VR/AR/MR), accurate eye tracking recently attracted considerable research interest - mainly because it enables many functions that significantly improve the performance and experience of VR/AR/MR headsets, such as foveated rendering, or compensating for the accommodation-convergence reflex. To estimate the gazing direction of the human eye, current approaches either utilize 2D features detected from 2D eye images, or exploit sparse reflections of a few point light sources at the eye surface ("corneal/scleral reflections"). The latter retrieves 3D surface information for an improved gazing direction calculation, albeit only at maximal ~10 surface points. In this contribution we introduce an approach that significantly increases the information content provided from corneal or scleral reflections by using Deflectometry to acquire a dense and precise 3D model of the eye surface. The acquisition of ~1 million surface points per measurement step is easily achievable with off-the-shelf hardware. We exploit the retrieved surface normals and dense 3D features estimated via deflectometry to accurately estimate the gazing direction.

## 2. Method and Results

Deflectometry is an established method in surface metrology to reconstruct the 3D surface of specular objects, such as freeform lenses, car windshields, or technical parts [1-3]: The reflection of a screen displaying a known pattern (e.g. a sinusoid) is observed after reflection from the specular surface under test. From the deformation of the pattern in the camera image, the normal vectors of the surface (and eventually the surface shape via integration) can be calculated. The inherent depth-normal-ambiguity is solved by adding a second camera, which results in a so-called "Stereo-Deflectometry" system [1]. Our proposed method utilizes Deflectometry for a dense and precise measurement of the eye surface. To calculate the gazing direction we first trace back the measured surface normal vectors towards the center of the eye. Due to the vastly different radii of cornea and sclera, the back-traced surface normals aggregate at two points inside the virtual 3D eye model: the center of the corneal sphere and the center of the scleral sphere (see Fig.1.c). Eventually, we calculate the

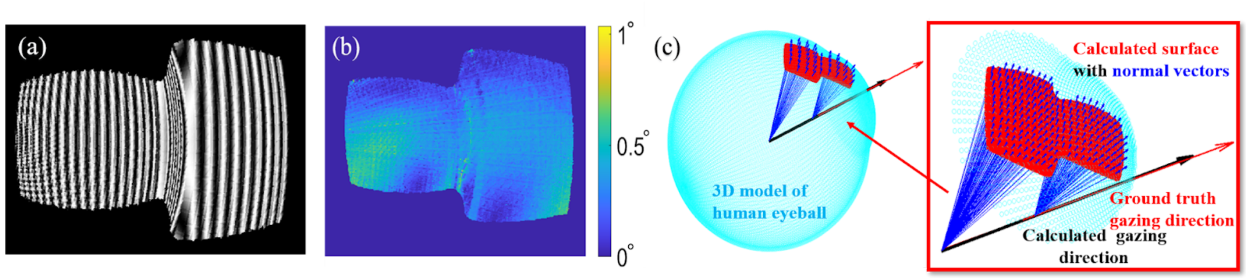


Fig. 1. Calculating the gazing direction using dense 3D surface measurements. a) Deflectometry measurement: Camera image of the sinusoidal screen pattern reflected from the eye surface. b) Error map: calculated normal map w.r.t. the ground truth (error in degrees). c) Calculation of the gazing direction by tracing back the measured surface normals to the scleral and corneal center.

gazing vector by estimating the sphere centers from the backtraced normals with a closest point algorithm.

We test the feasibility of our proposed method in simulation. We simulate a screen of size 10.6 cm by 6 cm and two identical cameras whose optical axes enclose an angle of 15°. A 3D model of a human eyeball is placed at 6 cm standoff to the screen. To achieve more realistic simulation results, we add 5% photon noise in our simulated camera images. The normal map of the eye surface is obtained from phase shifting sinusoidal fringes on the screen, and the surface shape is calculated from a combination of the Stereo Deflectometry algorithm [1] with iterative surface integration [4]. Eventually, the gazing direction is evaluated with the previously described approach. The results are shown in Fig. 1. The calculated gazing direction is recovered with an absolute error angle of *0.43°* relative to the ground truth gazing direction. Repeating the simulation experiment 96 times for randomized eye rotation angles delivers calculated gazing directions with an RMSE of *0.34°* with respect to the ground truth.

After demonstrating the feasibility of our method in simulation we show a first experimental result for the gazing direction calculation. Our prototype setup (see Fig. 2a) consists of two cameras (FLIR-fl3-u3-13s2c) and a 26cm x 12cm computer screen, with a geometrical arrangement similar to the simulated setup. The object is a realistic model of a human eye with elevated cornea (see Fig. 2b). The calculated 3D surface together with the captured surface normals and the evaluated gazing direction vector can be seen in Fig. 2c.

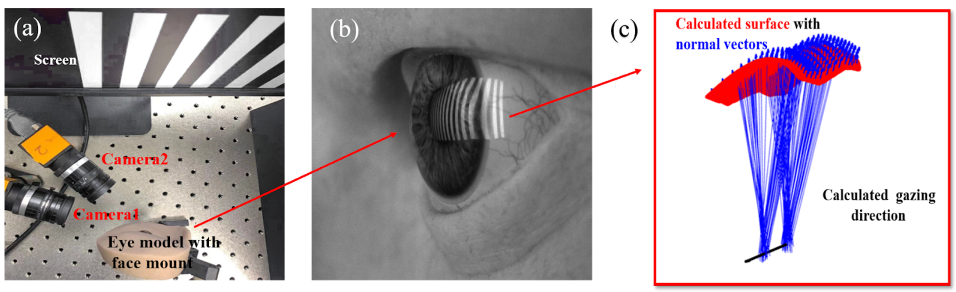


Fig. 2. First experimental results, acquired with our prototype setup. a) Photograph of the setup. b) realistic eye model with reflected screen pattern. c) Calculated 3D surface and surface normal vectors with evaluated gazing direction.

## 3. Summary, Discussion, and Outlook

We introduced a novel approach for eye tracking. The approach is based on acquiring dense deflectometric information of the eye surface and calculating the gazing direction from the measured surface normals. First simulation results are promising and deliver calculated gazing directions with an RMSE of only *0.34°* with respect to the ground truth gazing directions. A measurement procedure to quantify our real experiments with the prototype setup (where the ground truth gazing direction is unknown) is current work in progress. For an accurate result, the quality of the system calibration needs to be improved. Moreover, we are working on an extension of the method introduced in [5] to measure the gazing direction in single-shot. It should be emphasized that not all human eyes might have a perfectly spherical cornea and sclera surface. However, our gazing direction evaluation is estimated to deliver good results as long as the respective shapes of cornea and sclera are rotationally symmetric around the optical axis of the eye. In this case, all back-traced normals will meet along the optical axis (which defines the gazing direction) instead of at two distinct points.

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