Dual of Shack-Hartmann Optometry using Mobile Phones

Vitor F. Pamplona[1,2] **Ankit Mohan**[1] **Manuel M. Oliveira**[1,2] **Ramesh Raskar**[1]
[1] *Camera Culture Group - MIT Media Lab* [2] *Instituto de Informática - UFRGS*
{pamplona,ankit,manuelmo,raskar}@media.mit.edu

Abstract: We describe an optical design that retrofits a cell phone display and an interactive software for assessing refractive properties of human eyes. User evaluation revels an average error of ~ 0.5 diopters using currently available phones.

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1. Introduction

Uncorrected refractive errors are the second leading cause of blindness, which affects 2% of the world population. 87% of these individuals live in developing countries. Approximately two billion people worldwide have some sort of refractive condition. From those, 517 million suffer from near-vision impairment, which affects their daily lives [1]. Current means of measuring refractive eye conditions include Snellen charts, phoropters, retinoscopes, and refractometers. The operation of such devices require a trained technician, and none of them allow for self evaluation. Our system is based on Schneier principle [2] and Spatially Resolved Refractometers [3] but uses currently available cell phone displays as light sources to create the dual of Shack-Hartmann-based techniques [4]. The patient looks at a cell phone screen through a pinhole array at a very close range and aligns displayed patterns. The pinhole-LCD setup creates an equivalent of a parallax barrier display. Since the light rays from these patterns pass through different regions of the cornea/crystalline, the number of steps required for the alignments indicates the refractive errors. Our system is simple, cheap, enables self awareness of refractive conditions, and it is ideal for remote places, where even electricity may not be available.

Our contributions include: (i) the design of an optical probe using cell phone displays, pinhole arrays and interactive software (called NETRA); and (ii) validation of refractive assessment against subjects' current prescriptions.

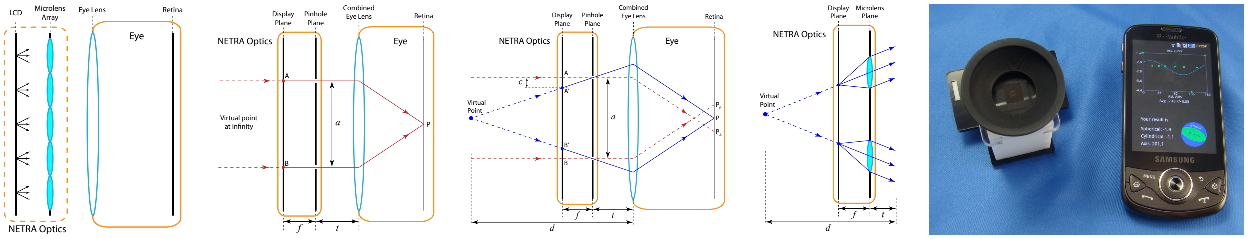
2. Optical Design and Interactive Software

We create virtual objects at different depths by placing a pin-hole array on top of the cell phone display (Figure 1). As we illuminate one point directly under each pinhole (points A and B), two parallel rays enter the eye simulating a virtual object at infinity. A normal eye converges the rays on the retina (Point P). A *myopic* eye, however, converges the incoming rays before the retina, and the user perceives two distinct spots (P_A and P_B), as shown in Figure 1(c). Via software, a myopic user approximates the spots until they appear to overlap (1D search). Hyperopes see "beyond infinity" when their crystalline lenses are relaxed. Moving those spots far apart on the screen will move them closer in the subject's view. The final distance between spots on the screen reveals the object's distance from the tester's eye. The device tests for the far sight, since the human eye tends to relax when looking through a pinhole [5]. Since convergence affects accommodation [6], pinholes and displays must be coplanar with the subject's image plane for the far field.

The amount of pixel shift c required to create a virtual source at a distance d from the eye is $c = f(a/2)/(d - t)$, where t is the distance from the pinhole array to the eye, a is the spacing between the pinholes, and f is the distance between the pinhole array and the display plane. f is also the focal length of the lenslets for a microlens-array-equivalent setup (Figure 1(d)). The bigger the f value, the dimmer the image. a is limited by pupil diameter. The power of the lens required to fix myopia (or hyperopia) is given (in diopters) by $D = (1/d) = 1000/(f(a/2)/c + t)$, where all distances are in mm. Positive values for c and D represent myopia, while negative values represent hyperopia.

Our prototype uses a Samsung Behold II, which has a display with 180 DPI, and a pinhole mask with $2mm$ hole pitch and hole diameter of $0.25mm$ at a distance of $f = 60mm$ and $d = 15mm$. This provide approximately 1.2 diopter per displaced pixel. We use 8 pinholes (3×3 grid without the central one) in order to test 8 meridians for the astigmatism case. The corrections required for each meridian are best fitted using the sin^2 function that defines astigmatic lenses $P(\theta) = S + C\, sin^2(\alpha - \theta)$, where S is the eye's spherical power, C is its cylindrical power, and α is the angle of the cylinder axis [7]. It follows that $min\,(P(\theta)) = S$, and $max\,(P(\theta)) = S + C$.

As the user moves the patterns, the distortion caused by an astigmatic lens is a 1D displacement of the pattern's center in the direction perpendicular to the testing meridian. Thus, we use symmetric patterns, such as lines segments, oriented perpendicular to the direction of motion.



(a) Optical Setup (b) Perfect Eye (c) Myopic Eye (d) Microlens (e) Optical Probe and Samsung Behold II

Figure 1: NETRA optical setup: (a) a microlens array placed over a high-resolution display is held right next to the eye. (b) The NETRA optical system using a pinhole array. A perfect eye converges parallel rays onto a point on the retina. (c) A myopic eye converges a set of parallel rays before the retina (red arrows). By shifting points A and B to A' and B', respectively, the resulting rays focus on the retina at point P (blue arrows). The amount of shift required to move A to A' allows us to compute refractive error. (d) Microlens design of the system improves the light throughput. (e) Current prototype uses the Samsung Behold II cell phone display and consists of a simple optical attachment costing less than USD 2.00.

3. Evaluation

The device was tested on 13 eyes (ages 19 to 30) and the results were compared against the subjects' prescriptions. For this experiment, the mean absolute error was 0.49 ± 0.08 diopters for spherical correction, 0.67 ± 0.029 for cylindrical correction, and 9.17 ± 0.75 for the axis of astigmatism. The mean absolute error of the spherical equivalent ($S_{eq} = S + C/2$) was 0.55 ± 0.02. No eye drops for relaxing accommodation were used. Instead, the subjects were instructed to look at far objects in the beginning of each meridian test. Intriguingly, the error decreases when we group only the data from non-dominant eyes: $S_{eq} = 0.36 \pm 0.007$ diopters.

4. Conclusion

We retrofit a cell phone display to create optometry device that estimates the wavefront aberrations of a subject based on user interaction, without moving parts, fundus cameras, or retinal illumination. The current device reaches 1.2 diopters in resolution and has an average error of ~ 0.5 diopters. Accuracy is expected to increase as technology evolves. Newer available mobile phone displays, such as the Nexus One, can achieve resolution of 0.5 diopters when using a $3mm$ pinhole pitch. Our device can be though as a thermometer for visual performance. The same way that the thermometer measures corporal temperature and does not prescribe medicine, our device will not replace the need for optometrists. We hope that our work can spur research in modern view-dependent high resolution displays and clever optics to improve self-awareness and health conditions in remote places of the world.

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