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WAVEFRONT SENSOR WITH CYLINDRICAL SYMMETRY AND PRELIMINARY COMPARISON WITH THE HARTMANN-SHACK SENSOR FOR VISUAL OPTICS APPLICATIONS

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Abstract: The development of the hardware and software of a novel wavefront sensing device is presented. The new sensor was manufactured using cost-effective materials. In order to compare the efficiency of this first prototype with the Hartmann-Shack (HS) sensor, theoretical simulations and practical measurements on a mechanical eye were taken. Overall theoretical/practical Zernike Coefficient (ZC) root mean square error (RMSE) for the HS and new sensor were 0.13/1.50 and 0.10/0.60 microns, respectively. RMSE compared to autorefractor for sphere, cylinder and axis, was 0.22D, 0.24D, 350 and 0.35D, 0.17D and 260, respectively. Results presented here clearly indicate that the new proposed sensor has equivalent results compared to the HS sensor and to the autorefractor. We also discuss here the potential benefits of this new sensor. Further tests should be implemented in order to verify if these potential benefits may be reverted into more precise and better cost-effective sensors.

Keywords: Optical sensor, Adaptive optics, Zernike coefficients, Zernike Polynomials, Autorefractor, Optical aberrations, Hartmann-Shack

Introduction

The Hartmann-Shack sensor has long been applied in the fields of optical engineering [1, 2] with quite impressive performances when used in astronomical telescopes on earth and in space (the Hubble telescope). More recently the HS sensor has shown to also be effective in visual optics [3, 4, 5]. When used in conjunction with adaptive optics systems it allows for the correction of low and high order aberrations, significantly improving image quality.

Although very effective, the HS sensors available today have their prices exponentially increased depending on the number of lenticules. This is due to the electro-chemical processes usually applied in their manufacturing. Moreover, the Cartesian symmetry of conventional Hartmann screens is very suited for on-axis optical systems. When applied to the *in vivo* visual system, which is a naturally decentered system, a rotationally symmetric disc-shaped system may be more adequate and easy to align with the eye's entrance pupil.

The development of a new type of optical sensor is presented here. It has a cylindrical symmetry and uses more cost-effective material and manufacturing methods than usual HS sensors. It also presents a much greater resolution than HS and other sensors. Preliminary tests in visual optics are presented here and potential advantages are also discussed.

Material/Methods

In Figure 1 we have a diagram and magnified photographs of the new optical sensor.

Each half toroidal surface works as a "donut" shaped lens that is continuous in the polar direction. When light incoming from the wavefront hits the sensor, a series of concentric disks are formed on the focal plane; they will be uniformly or non-uniformly distributed depending on the aberrations contained in the wavefront phase; the same happens for Placido disks of a videokeratographer [8, 9] reflecting on a regular or distorted cornea, with the obvious difference that on the cornea light is reflected and at the sensor it is being refracted.

Image-processing and Zernike fitting algorithms were implemented based on previous work [6-9]. The cylindrical symmetry of the new sensor required a slightly different Least Squares fitting algorithm when compared to conventional HS, because there is no information regarding polar shift; there is only information regarding the radial slopes. In order to verify if the radial slopes were also sufficient for precisely recovering non-rotationally symmetric surfaces, a series of theoretical aberrated wavefronts were generated containing low and high order Zernike terms. This data was input into the algorithms of the new sensor and those of the conventional HS sensor and root mean square error (RMSE) using the first 15 VSIA Zernike Coefficients were 0.13 and 0.10 microns, respectively. After verifying that the new sensor worked synthetic surfaces, it was tested in practice.

The new sensor was installed in the optical setup shown in Figure 2.

A series of 10 images for defocus aberrations ranging from –5D to 5D, in steps of 1D, were acquired and input into the image-processing and Zernike fitting algorithms.

Results

Figure 3 presents the RMSE for each aberration for each sensor when compared to the autorefractor as control. Overall mean of the RMSE was 1.50 and 0.60 microns, for the HS and new sensor, respectively. Table 1 presents the RMSE for the sphere-cylinder values, again for the autorefractor as control.

Discussion

The overall RMSE for both sensors when theoretical aberrations were used as control was 0.13 microns for the HS and 0.10 microns for the new sensor. Mean overall value of the absolute deviation between sensors was 0.08 microns. These overall values demonstrated that both sensors have very similar performance for all theoretical surfaces.

Practical results for both sensors are shown in Table 1. The RMSE of the autorefractor when the calibrated aberration on the mechanical eye is taken as control was 0.11D, 0.08D and 17^0 for sphere, cylinder and axis, respectively.

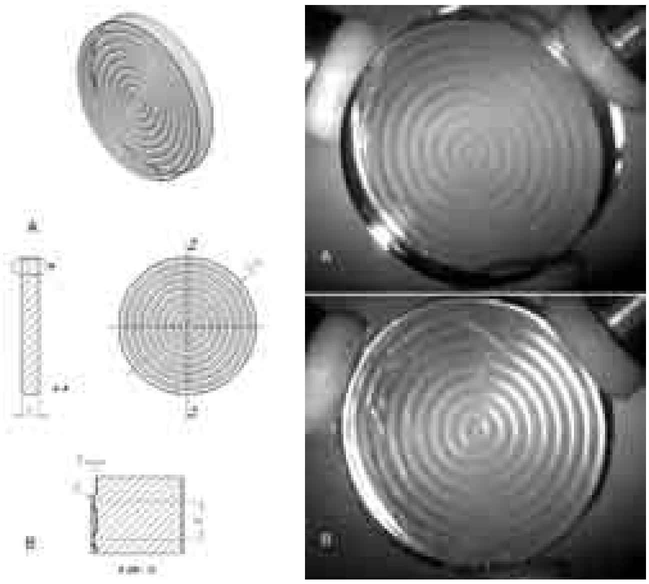

Figure 1. (A) Perspective and (B) frontal views of an (left) AutoCAD (Autodesk, San Rafael, CA) diagram of the proposed sensor and (right) actual photographs of the proposed sensor.

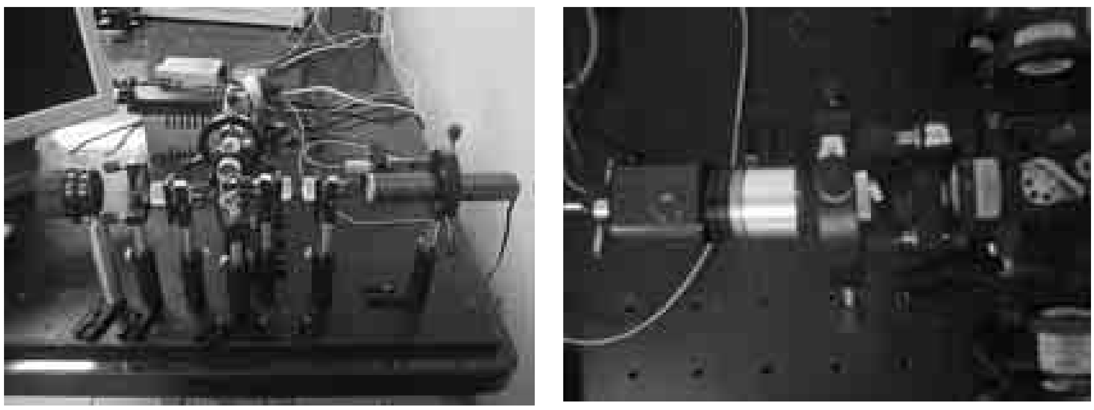

Figure 2. (left) Photograph of the actual optical system mounted in our laboratory and (right) detail showing the aluminum peace which attaches to the CCD and can hold either sensors, allowing for interchange without modifying the optical setup. For more details on the optical setup please refer to [5].

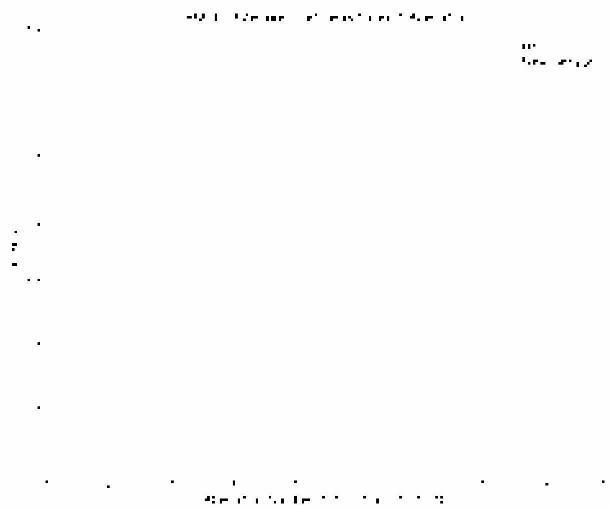

Figure 3. Root mean square error (RMSE) for all Zernike coefficients.

A reasonable assumption is that our mechanical eye was calibrated and deviations for the autorefractor are intrinsic of its measurements, since the deviation was very close to deviations of different autorefractors for the *in vivo* human eye (±12D) [10]. In this sense results for sphere in Table 1 may be added approximately ±0.11D, which, for a negative value, tell us that absolute error may be as low as approximately 0.11D and 0.24D for the HS and new sensor, respectively. These results are generally accepted for prescription and visual acuity tests [10].

Table 1.

RMSE for Sphere-Cylinder equivalents

RMSE for all sphere-cylinder parameters for each sensor when compared to the autorefractor data. Autorefractor RMSE when mechanical eye is taken as control was 0.11D, 0.08D and 17^0 for sphere, cylinder and axis, respectively.

	Sphere (D)	Cylinder (D)	Axis (degrees)
HS	0.22	0.24	35
New sensor	0.35	0.17	26

Although the ideal procedure is to test any new sensor on several controlled aberrations, it is shown here that this new sensor is theoretically equivalent to conventional HS sensors. Moreover the preliminary results for a mechanical eye were very close to the results presented by both a conventional autorefractor and a HS sensor.

Possible advantages of this new sensor, which are yet to be addressed, include: easier alignment with the entrance pupil of the *in vivo* eye, which is the correct reference since the line of sight passes through this point; flexibility of resolution modification during the image-processing phase without the need to install different sensors on any wavefront sensing instrument – this would allow for this sensor to work as a conventional wavefront sensing device or a simple 3 axis autorefractor, much in the same way the modern videokeratographer renders precise software simulated values of conventional keratometry measurements [8, 9]; finally, price of production is in the order of 100 times less than HS sensors produced using typical electro-chemical processes.

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