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Corneal Topography based on The Compact Conical Null-Screen for a Mobile Device and Single Board Computer

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Abstract. We evaluate a spherical reference surface, with a compact null-screen corneal topographer, which is powered by a coupled mobile device. Alternatively, it is shown that the corneal topographer can be designed by using a camera module and a single board computer.

Keywords: Corneal topography, null-screens, optical metrology, aspherical surfaces.

1 Null-Screen Test

To obtain the shape of human corneas we use a compact null-screen placed in front of the eye formed by an array of spots at $\mathbf{P}_1$ where light rays travel to the surface at $\mathbf{P}_2$ to be reflected by the cornea, the rays pass through an aperture and lens at $\mathbf{P}$ to finally arrive at the image plane on $\mathbf{P}_3$ (see Fig. 1) by a CCD/CMOS sensor. The optical system at $\mathbf{P}$ is used to focus the light rays on the sensor, the diaphragm is large enough for the test to be in the geometrical optics regime. Additionally, the lens can create some distortion at the obtained image that can be corrected.

1.1 Corneal Topography

To measure the cornea, we obtain an approximated normal field to the surface by joining the points on the null-screen and on the sensor with the incident and reflected rays:

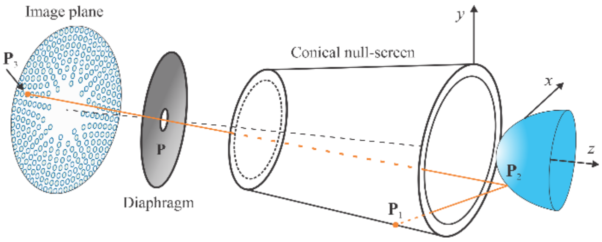


Fig. 1. Null-screen test for a surface.

$$\mathbf{N}_a = \frac{\mathbf{R}-\mathbf{I}}{|\mathbf{R}-\mathbf{I}|}. \quad (1)$$

The direction of the reflected vector is known **R**=**P**$_1$ -**P** (see Fig. 2) and to obtain the incident vector we use a decentered and tilted reference surface such as:

$$z = \frac{r - \{r^2 - Q[(x-x_0)^2 + (y-y_0)^2]\}^{1/2}}{Q} + A(x-x_0) + B(y-y_0) + z_0, \quad (2)$$

where r is the radius of curvature, $Q=k+1$ where k is the conic constant, x_0, y_0 and z_0 are the decentering coordinates of the surface, A and B are the tilt.

The shape of the test surface can be obtained with the formula:

$$z - z_i = \int_{P_i}^{P_f} \sqrt{\left(\frac{n_x}{n_z}\right)^2 + \left(\frac{n_y}{n_z}\right)^2}\, d\rho, \quad (3)$$

where z_i is the sagitta for one point of the surface, and n_i ($i=x,y,z$) are the components of the normal field that was obtained in advance. This is an exact expression, and it is discretized using the trapezoidal rule for non-equally spaced data.

With the normal field we can obtain geometric parameters of the surface such as the radius of curvature and the conic constant by fitting the data to:

$$\eta \equiv \left(\frac{n_x}{n_z}\right)^2 + \left(\frac{n_y}{n_z}\right)^2 = \frac{x^2 + y^2}{\{r_{fit}^2 - (k_{fit}+1)(x^2+y^2)\}^{\frac{1}{2}}}, \quad (4)$$

where r_{fit} is the vertex radius of curvature, k_{fit} is the conic constant.

2 Results

2.1 Calibration of the System

We used a compact conical null-screen powered by a mobile device's camera that captures the reflected pattern. The design parameters are given in table 1. We consider a spherical reference surface, a CMOS sensor with a sensitive area of 5.64 mm x 4.23

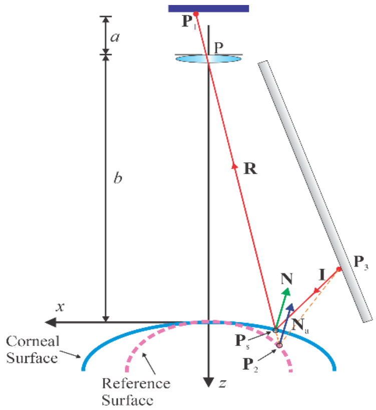


Fig. 2. Approximation of the normal field.

Table 1. Conical null-screen design parameters.

Element	Symbol	Size (mm)
Surface radii of curvature	*r*	7.8
Surface diameter	*D*	12
Camera lens focal length	*f*	4.2
Image diameter length	*d*	0.86
Diaphragm-Sensor distance	*a*	5.2
Diaphragm-Surface vertex distance	*b*	70
Cone height	*h*	85.50
Cone radius	*s*	16

mm (4032x3024 pixels) with a 4.2 mm focal length lens attached, and the morphology of the human face.

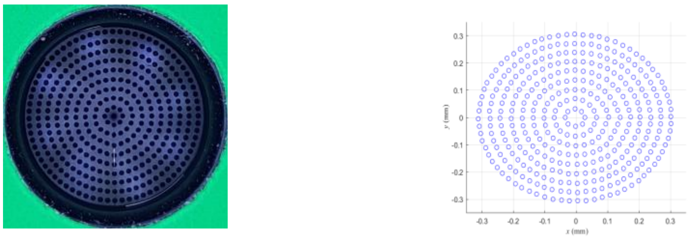
The alignment of the camera, corneal topographer, and test surface at the optical axis of the entire system is important to obtain reliable results.

To calibrate the system, we use a spherical reference surface with radius of curvature r=7.8 mm and effective diameter D=12 mm and calculate the center of mass for each detected spot on the sensor with an image-processing program (see Fig. 3).

Then, we placed a grid distortion test targets at 3.69 mm from the conical null-screen, i.e., where the reflected image is formed to measure their radial distances on the grid and on the sensor to obtain the transverse magnification and radial distortion of the lens by fitting (see Fig. 4):

$$\rho_o = \frac{\rho_d}{M_T} - \frac{E}{M_T^4}, \tag{5}$$

where ρ_o is the object radial size, ρ_d is the radial distorted image, M_T is the transverse magnification and E is the lens radial distortion. This last parameter allows to correct the image and obtain more accurate data.



(a) (b)

Fig. 3. a) Reflected null-screen on the reference surface, b) calculated centroids.

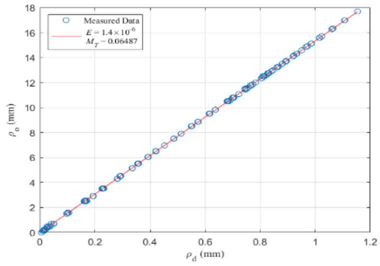


Fig. 4. Fit of the lens radial distortion.

Table 2. Values recovered analyzing the corneas as aspherical surfaces.

Surface	*r* (mm)	*k*	x_o (mm)	y_o (mm)	z_o (mm)	*A*	*B*
Reference Sphere	7.81	0.02	0.13	0.04	2.62	0.0145	0.0036
Right Cornea	7.84	-0.76	-2.18	1.74	2.57	-0.1593	0.2484
Left Cornea	7.89	-0.91	1.50	4.68	4.40	0.0561	0.5796

After distortion correct the data, we obtain the elevation map for a reference surface with the best fit surface (see Fig. 5a) and obtained its geometrical parameters using Eq. 2 (see Table 2 first row) where we notice the radius of curvature to be *r*=7.81 mm that has an error of 0.13% compared to the design value.

After calibration, we obtained the same map (see Fig. 5b and 5c) and parameters for two human corneas, and the *rms* difference of sagitta. In Table 2 we show the recovered radius of curvature and conic constant for each surface.

We notice that for every map the *rms* difference un sagitta is about some μm which can be compared to those of commercial topographers of about 5-10 μm.

2.2 Corneal Topography with a Single Board Computer

The compact corneal topographer can be adapted to couple a camera module of a Single Board Computer (SBC) and obtain high quality images (see Fig. 6). The camera has a 3.68 mm x 2.76 mm (3280 x 2464 pixels) sensor image area, and a 3.60 mm focal length. Due to its small size and focal length it has to be focused manually which makes it hard to focus at the required distance.

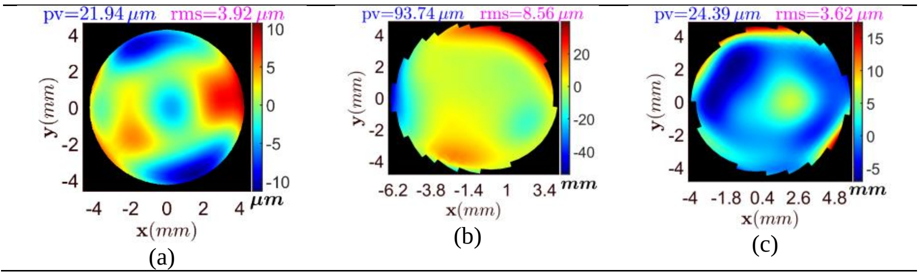


Fig. 5. Elevation maps for: a) reference surface, b) right cornea, c) left cornea.

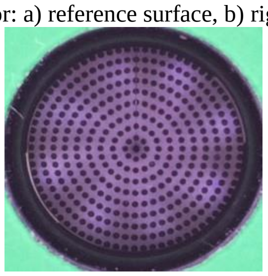


Fig. 6. Reflected pattern detected by the camera module.

The same methodology mentioned before can be applied for this device, and the lens radial distortion can be measured to correct the reflected image and obtain the corneal topography.

3 Conclusions

The compact corneal topographer can be used by any small device. We recovered some geometrical parameters with high accuracy of a reference surface and two human corneas. We need to calibrate this device by aligning the entire system, measuring the lens radial distortion and by obtaining the shape of a reference surface, in our case we used a sphere with radius of curvature r=7.8 mm and recovered a value with 0.13% error. The use of an SBC for a compact conical null-screen corneal topographer can improve the design of a new device due to its portability and easy programming.

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