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10—4 3D Fundus Shape Reconstruction and Display from Stereo Fundus Images

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Abstract

A new method to recover and display 3D fundus shape, inner bottom shape of eye-ball, from stereo fundus image pair is developed. For the fundus stereo images, a simple stereo technique does not work, because the fundus is observed through eye lens and a contact wide-angle enlarging lens. In this method, utilizing the fact that fundus forms a part of sphere, we identify their optical parameters and correct the skews of the lines-of-sight. Then, we obtain 3D images of the fundus by back-projecting the stereo images.

1 Introduction

In this paper, we propose a new method for 3D reconstruction and display a fundus, inner bottom of an eye-ball, shape from its stereo images.

Fundus is only a part where human internal blood vessels and nerves can be observed directly from outside of the body. So that, the observation of the fundus is useful not only for diagnosis of eye diseases but also for checking whole body conditions. However, it has been said to be difficult to show 3D position of the region of interest for orientations between doctors, even from the stereo images because of the reasons above mentioned. Our new method takes into account of the skew of the lines-of-sight by the incidental lenses and correct them, then, gives reconstruction of the 3D fundus shape and display its pattern in 3D form.

A pair of stereo images are taken by shifting fundus camera with a small amount. For this stereo pair, however, a simple stereo technique does not work for the 3D reconstruction, because the fundus is observed through eye lens and, sometimes, a contact wide-angle lens for enlarging the viewing field. Moreover, the optical system of the fundus camera produces high distortions of image because it employs a specialized optical mechanism. This distortion can be corrected once the camera optical system has been calibrated. But, the optical properties of human eyes are different from one to one, individually, and also from time to time, and hard to be calibrated.

In our method, first, the combination of the eye lens and the contact enlarging lens is modeled with a single simple lens. Then, taking into account of the fact that the fundus shape (the eye-ball shape) can be considered as a sphere, we identify the optical parameters of the model single lens. At the same time, we reconstruct the 3D fundus shape applying these identified optical parameters for the stereo optics.

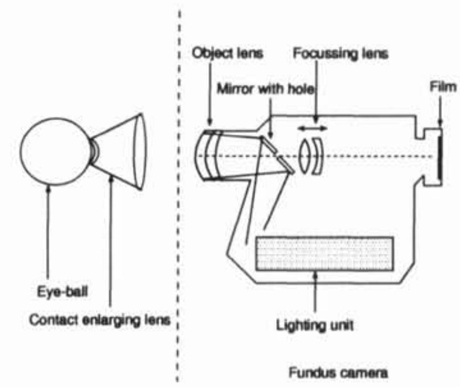

Fig. 1: Optical system of fundus camera and human eye

2 Principles of the Reconstruction

Figure 1 shows the optical arrangements of the fundus camera, the contact enlarging lens and the eye lens. Viewing field of fundus images with respect to eye center is usually 50[degree]. The contact enlarging lens is not always used.

In our system, the optical system of the fundus camera has been calibrated by the two-plane method proposed by the authors[1]. This paper skips the detail of the calibration method.

Actual eye shapes have a small skew from sphere, but the fundus, the bottom part of the eye, can be considered as a part of a sphere. If the combination of the eye lens and the contact enlarging lens

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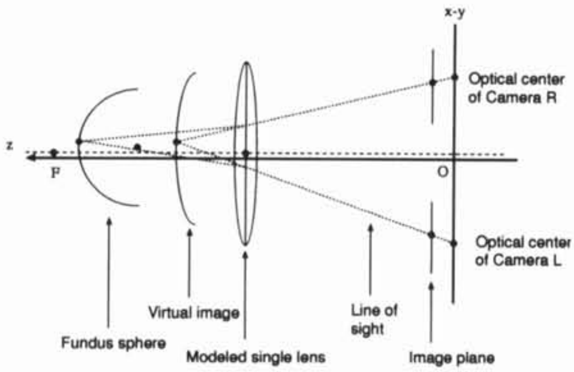


Fig. 2: Optical model for stereo fundus images (without contact enlarging lens)

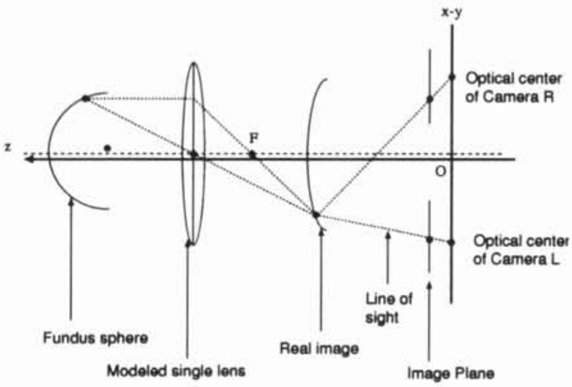


Fig. 3: Optical model for stereo fundus images (with contact enlarging lens)

can be modeled with a single simple lens, the spherical shaped surface of the fundus is mapped onto a quadratic surface as its real image. For the case without the contact lens, it is mapped onto also a quadratic surface but as a virtual image. The shapes we observe from fundus stereo images through the eye lens with/without contact enlarging lens are just these quadratic surfaces. Figure 2 and 3 show the schematics of these imaging mechanisms.

It should be noted that the surface we can reconstruct from the correspondences of image point pairs in the stereo fundus images is this virtual quadratic surface. But, once this surface is reconstructed, assuming that it is just the image of a spherical surface by a single lens, we can identify the optical parameters of the lens which should produce the quadratic surface. At the same time, we can also identify the sphere parameters which should be the original fundus shape.

3 Algorithm

3.1 Geometry of the optical system

Now, we describe more details of the reconstruction algorithm for the case with contact enlarging

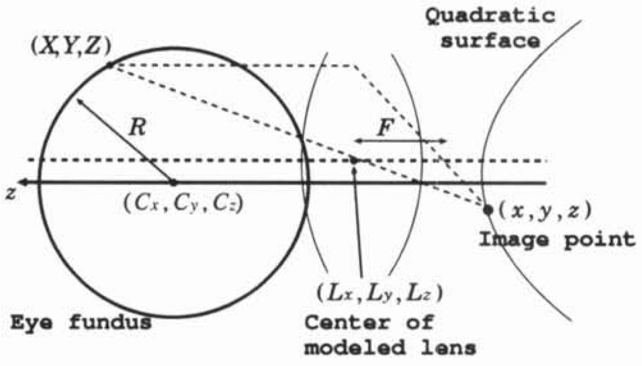


Fig. 4: Coordinate system and parameters for the modeled optical system of the eye lens with the contact enlarging lens

lens (Fig.3). Let us define above mentioned parameters as shown in Fig.4.

(L_x, L_y, L_z) is the center of the modeled single lens, and F is its focal length. (C_x, C_y, C_z) is the center of the modeled fundus sphere, and R is its radius.

Denoting a point on the fundus sphere with (X, Y, Z) and its image by the lens with (x, y, z) as shown the figure, we have the relations between them as,

$$\begin{aligned} x &= L_x - F\frac{X - L_x}{Z - (L_z + F)} \\ y &= L_y - F\frac{Y - L_y}{Z - (L_z + F)} \\ z &= L_z - F - \frac{F^2}{Z - (L_z + F)} \end{aligned} \tag{1}$$

Because that (X, Y, Z) lies on the fundus sphere, it holds

$$(X - C_x)^2 + (Y - C_y)^2 + (Z - C_z)^2 = R^2 \tag{2}$$

On the other hand, its image (x, y, z) lies on a quadratic surface, that is,

$$x^2 + y^2 + pz^2 - 2axz - 2byz - 2c_x x - 2c_y y - 2c_z z + k = 0 \tag{3}$$

This means that, once the quadratic surface (3) has been reconstructed from the fundus stereo pair, by using (1) and (2), the parameters of the modeled fundus and single lens can be derived from the coefficients of this quadratic surface.

We have 7 coefficient parameters in (3), while the number of the parameter to be identified is 8. This means we can reconstruct fundus shape up to a scale. This ambiguity is essential for the case where the focal length of modeled virtual single lens is left to be unknown. But, in our application, the absolute scale of the reconstruction is not needed. If needed, because we are able to have the fundus radius R

easily by a commonly available equipment, it may be resolved by this measurement.

The realization of the fundus shape reconstruction from the image surface is given as followings:

Firstly, F and L_z must holds

$$(a^2+b^2-p)(L_z-F)^2+2(c_z+ac_x+bc_y)(L_z-F) \\ +F^2+c_x^2+c_y^2=k \quad (4)$$

or

$$L_x^2+L_y^2-p(L_z-F)^2+2c_z(L_z-F)+F^2=k \quad (5)$$

Then, the rest parameters will be given as,

$$\begin{aligned} L_x &= a(L_z-F)+c_x \\ L_y &= b(L_z-F)+c_y \\ C_x &= c_x+aL_z \\ C_y &= c_y+bL_z \qquad (6) \\ C_z &= (1+p-a^2-b^2)L_z+ \\ &\quad (1-p+a^2+b^2)F-(ac_x+bc_y+c_z) \\ R &= \\ &\sqrt{(a^2+b^2-p)(k-c_x^2-c_y^2)+(c_z+ac_x+bc_y)^2} \end{aligned}$$

For the case without the enlarging lens shown in Fig.2, almost the same relations are given.

3.2 Iterative parameter fitting algorithm

As described, the fundus shape can be reconstructed from the stereo pair images, in principle. Here we propose a practical algorithm to identify the above mentioned parameters. A point on one of the stereo images corresponds to a line of sight in the space in front of the camera. By following those lines of sight of the stereo fundus image points, we recover those parameters with an iterative optimization.

All the pairs of lines of sight of corresponding point pairs of the stereo fundus images must encounter each other on the sphere of the fundus after refracting at the modeled single lens. Using this fact, we optimize the parameters so that all the pairs of the crossing points of the pair of the lines of sight on the sphere become nearest. Total number of the parameters to be identified is 8.

As shown in Fig.5, a pair of corresponding lines of sight are refracted at the modeled lens, respectively, then run across the sphere. We denote the distance between the respective crossing point of the i-th pair on the sphere as d_i. Then, we optimize all the parameters defined above so as to minimize $D=\sum_i d_i^2$ by an iterative method. In this work, we employed the Powell method. Among the parameters, the eyeball radius R can be measured by an ultra-sonic instrumentation. We used this measurement for initial value of the iteration.

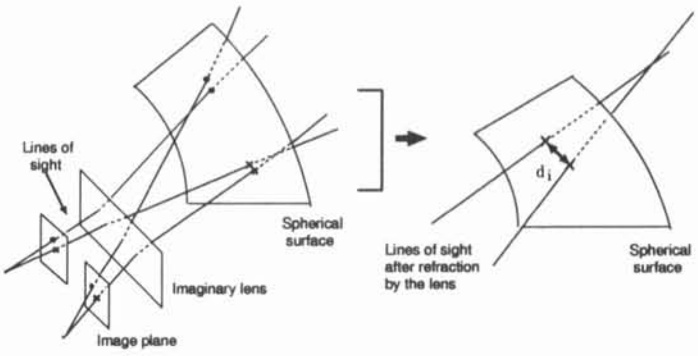


Fig. 5: Criterion for the parameter fitting

Table 1: Parameter values used for image synthesis and their reconstruction

Parameters	Original	Reconstructed
F	120	118
R	100	102
C_x	0	11.0
C_y	0	-1.38
C_z	600	594
L_x	0	4.42
L_y	0	-0.581
L_z	400	390

4 Experimental Results

Firstly, we show an experiments using synthesized images to confirm the basic principle of the reconstruction.

We synthesized stereo pairs of fundus images. We assumed that points were arranged on a fundus sphere as shown in Fig.6. We also assumed the refractive index of eye lens to be 1.336, and the stereo images were taken by a camera with the focal length $f=20$mm and the base line width $d=4$mm. Then, a pair of stereo image shown in Fig.7 was obtained. On these images, noises with 1 pixel length standard deviation were added.

From this stereo image pair, we reconstructed the fundus shape as shown in Fig.8. Original points and their reconstruction are superimposed in the figure.

Table 1 shows parameter values used for image synthesis and their reconstruction. The corresponding values agree with each others.

Figure 9 shows an example of a real stereo pair of the fundus images. Among these images, about 300 corresponding point pairs were extracted automatically by a method developed by the author[2]. Those corresponding points are shown in Fig.10.

From these point pairs, the lens optical parameters and the fundus shape were identified. Figure 11 shows the 3D displays of the reconstructed fundus shape on which the fundus patterns were back-

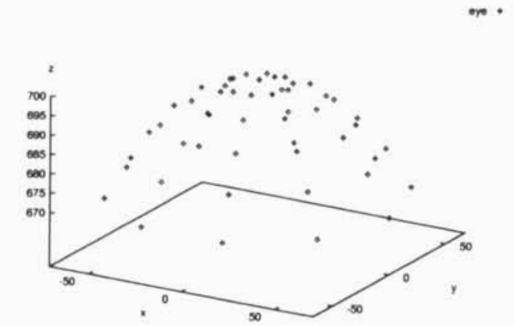


Fig. 6: Point arrangements on the fundus sphere for synthesized images

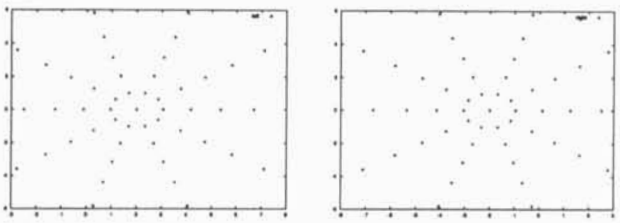


Fig. 7: Synthesized stereo fundus image pair

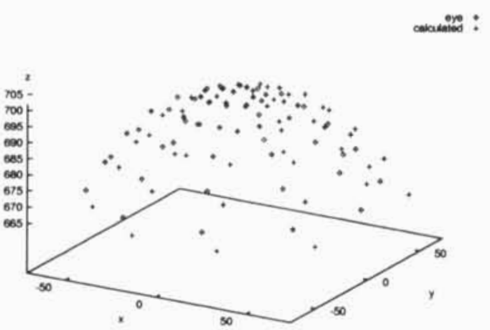
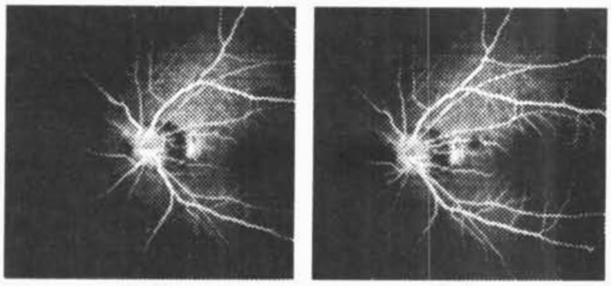


Fig. 8: Reconstructed and original point arrangements

projected from the images. This shows the feasibility of our new method.

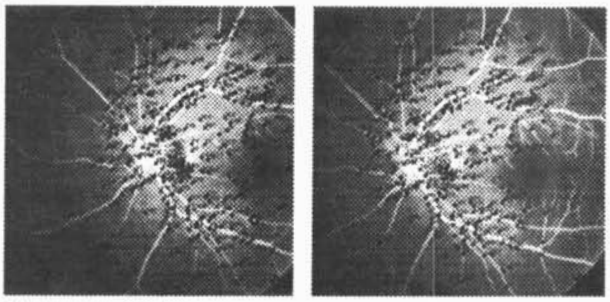
5 Conclusions

We have proposed new image processing technique for fundus image analyses. Experimental results promise its application for real fundus images. We believe this results much help in their diagnosis. We are now working on extensive accuracy and performance evaluations for effective computations.



Left Right

Fig. 9: Stereo fundus image pair



Left Right

Fig. 10: Corresponding points in the stereo fundus image pair

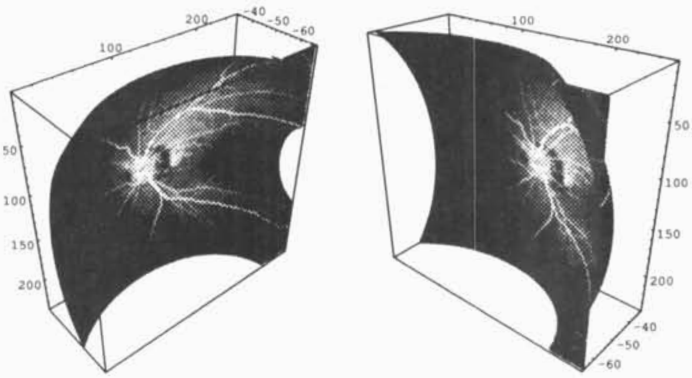


Fig. 11: 3D displays of the reconstructed fundus shape

References

[1] Deguchi, K. and Morishita, I. : A Unified Linear Camera Calibration Method Using Two Parallel Calibration Planes, *Trans. of the Society of Instrument and Control Engineers*, Vol. 29, No. 9, pp. 1023-1032 (1993).

[2] Deguchi, K.: Geometry of computer vision (2) – Mechanism of stereo –, *Journal of Information Processing Society of Japan*, 37-7, pp.662-670 (1996) (in Japanese)