Research Article

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Single-shot phase-measuring deflectometry for cornea measurement

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Abstract: Phase-measuring deflectometry (PMD) has become a standard tool to measure the topography of specular surfaces. We implemented PMD for the measurement of the human cornea topography, exploiting an earlier idea of Lingelbach et al. Two problems occur: a large angular dynamical range and a single-shot measurement are required. We solve these problems by an optimized geometry with minimal occlusion and by single sideband demodulation with a pre-distorted fringe pattern with optimal fringe period. An *in vivo* measurement of an astigmatic cornea displays a deviation from the medical diagnosis of only 0.15 D, which is within the medical quantization step of 0.25 D.

Keywords: corneal topography; metrology; three-dimensional sensing.

1 Introduction

We will discuss the implementation of phase-measuring deflectometry (PMD) [1] for the measurement of the human cornea. Deflectometry is well established to measure smooth specular surfaces. For cornea measurements, however, several problems have to be overcome: a large slope range is required, the small radius of the cornea introduces geometrical constraints, and eye movements require a single-shot method. Lingelbach et al. already proposed and implemented *in vivo* measurements of the cornea [2, 3], exploiting single-shot deflectometry via single sideband demodulation of a pre-distorted pattern. We will exploit these ideas too, aiming for an optimized implementation of deflectometry, with a large angular range of ±29°, a field of view of more than 7 mm, a central obscuration of only 0.4 mm, a high lateral resolution with the maximum possible fringe frequency, and with submicron accuracy.

As the cornea is responsible for about 70% of the eye's refractive power, knowing its topography is important for the ophthalmologist. Several methods and instruments are available to measure the cornea [4]. The most widely applied tools are 'keratoscopy' and the 'slit-based system', which both display severe limitations.

As PMD, keratoscopy is a deflectometric principle: it works by observing images of patterns (here concentric rings), reflected from the cornea. From the deformation of these images, deviations from the regular-shaped cornea can be detected. Keratoscopy [5, 6] evaluates only about 60% of the total cornea area [7]. The central region and the area between the rings cannot be measured. As the observed pattern is a ring system, only meridional components of the slope can be measured, and errors occur when the true corneal shape does not display rotation symmetry. The trueness and precision leave room for improvement.

The 'slit-based system' is not based on deflectometry, but on triangulation. A sharp and bright image of a slit is projected onto the cornea surface. This projected image at the (weakly scattering) cornea is observed (not the reflected image) via an angle of triangulation. Projection and observation are not coaxial. From the curvature of the observed slit image, the cornea shape along the illuminated section can principally be acquired. A full field measurement requires scanning and compensation of eye movements.

A single-shot method providing locally resolved and accurate full field data is required. We adapted PMD exploiting and extending the earlier idea of Lingelbach et al. [1] to measure the cornea. In this paper, we will discuss the challenges, which are the large curvature of the cornea (≙ large angular dynamic range), severe geometrical constraints, motion blur, low fringe contrast,

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calibration, and how to solve these problems, aiming for an optimal solution, in terms of accuracy, angular range, lateral resolution, and low obscuration.

Like keratoscopy, PMD exploits the image of a pattern that is reflected at the surface under test. By a proper sinusoidal pattern, PMD allows to analyze the fringe phase in each image pixel of the cornea [8].

Exploiting this information and with careful calibration, the local gradient of the surface can be calculated. The topography follows from integration [9] and the curvature from derivation. As PMD has been proven to be a valuable tool for many kinds of specular surfaces [10], it should be a proper tool for cornea measurement as well. However, we are facing the challenges mentioned above.

2 Solutions

2.1 Geometry

As the required angular dynamic range for the input rays is about ±58°, the common off-axis geometry of PMD is inappropriate. We designed an on-axis geometry as shown in Figure 1.

The on-axis geometry creates a new problem: the observing camera will occlude a central part of the pattern (there is no space for a beam splitter). This is a common problem of other methods as well. We minimize this obscuration to 0.4 mm by a small planar mirror mounted at the center of the screen. It sends the reflected image to the camera located beside the screen.

Figure 2 illustrates the geometrical relations: The field width X_1 is given by medical requirements to be about 7 mm. The mirror size D_{SP} should be as small as possible to avoid obscuration, but big enough to transmit all

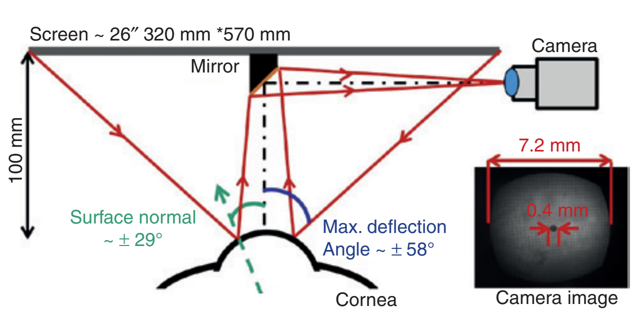

Figure 1: Phase-measuring deflectometry (PMD) with on-axis geometry, designed for large field (7.2 mm), large slope range (± 29°), and minimal central obscuration (0.4 mm).

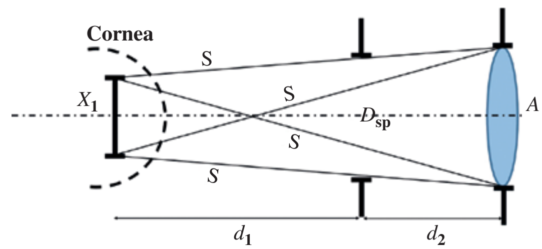

Figure 2: Mirror in the optical path: X_1 is the field width of the virtual image of the pattern behind the cornea, A is the aperture of the camera, D_{sp} is the diameter of the mirror, d_1 is the distance between the eye and the mirror, and d_2 is the distance between the mirror and the camera objective.

rays necessary for field and aperture A, without vignetting. The aperture should be as large as possible for high brightness, and high lateral resolution, but small enough to see the reflected pattern and the cornea at the same time.

We just present the results of this optimization; more details can be found in Reference [11]. A 26″ LCD monitor is placed at close distance (100 mm) to the cornea, to allow for an extremely large angular range of illuminating rays (116°) as shown in Figure 1. With the described geometry, we acquire a cornea field of 7.2 mm and a slope range of ±29°, for a cornea with a radius of curvature of 7.5 mm. A mirror with optimal diameter of 10 mm is mounted at the center of the screen. The mirror obscures a certain area of the screen, but the mirror image is strongly de-magnified by the cornea, and only 0.4 mm of the measured cornea field is missing. This is shown in the camera images of Figures 1 and 2.

2.2 Single shot measurement

The involuntary eye movements enforce a single-shot measurement, which makes PMD difficult: First, we have to acquire two components of the gradient. Second, the commonly used temporal phase shifting is not applicable. As Lingelbach et al. [1, 2] and Liu et al. [12], we exploit the single sideband method first described by Takeda [13]. The method allows for a measurement of the gradient with one single exposure.

However, single sideband demodulation requires a narrow bandwidth image to avoid mixing of the signal with the base band. Unfortunately, the observed fringe pattern is strongly distorted (Figure 3B) after reflection at the cornea. Its Fourier spectrum (Figure 3C) displays that it is not a narrow band. A further disadvantage of the distortion is shown in Figure 3B: The observed

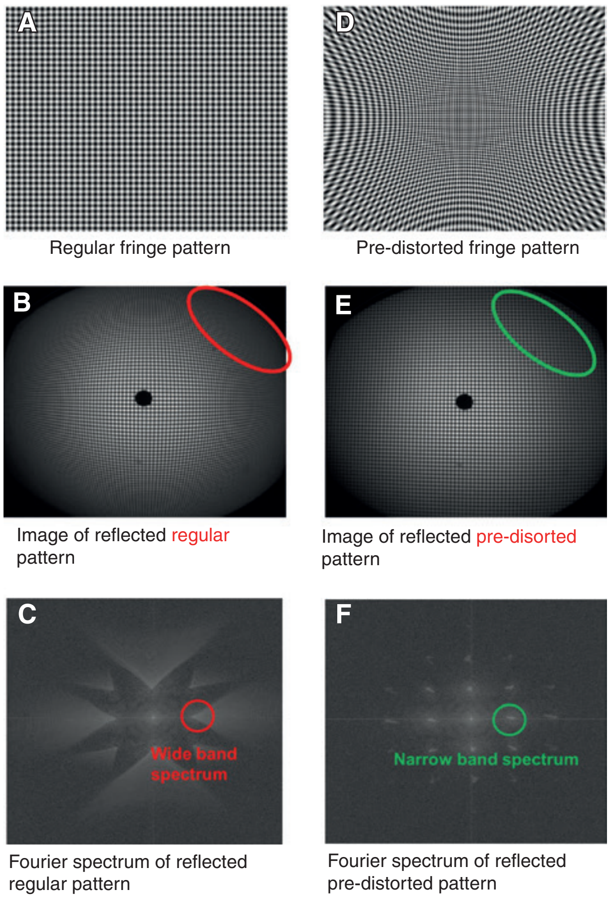

Figure 3: Projected patterns, camera images, and Fourier spectra with regular pattern (A, B, C) and with pre-distorted pattern (D, E, F).

fringes in the peripheral area are very dense, displaying low contrast.

Both problems are overcome by a proper pre-distortion of the input fringe pattern. As different corneas vary just slightly, an input fringe pattern can be designed, which generally results in a narrow bandwidth-reflected fringe pattern. Such a pre-distorted fringe pattern, calculated from a spherical 'reference cornea' is shown in Figure 3D, with its regular high-contrast reflected image, displayed in Figure 3E. Its narrow band Fourier spectrum is displayed in Figure 3F.

2.3 Optimal fringe period

In order to minimize phase errors, the fringe period has to be carefully chosen. The fringe period should be as small as possible (high carrier frequency, far away from the base band) but big enough to avoid low contrast and undersampling by the camera. A high fringe frequency allows as well for a high precision of the slope measurement. We resolve a fringe frequency of 12.5 periods/mm in the image reflected by the cornea. The optimal fringe period was experimentally found [11]: The best repeatability and best trueness is achieved with a fringe period of 8 pixels, in agreement with Ref. [12].

2.4 Eye positioning

It is well known that PMD can easily detect very small local slope variations. The real challenge is to achieve global trueness, which requires sophisticated calibration [14]. In our device, the major source of error is the distance between the cornea and the camera lens. Measurements of a bearing ball dummy with known radius (not shown here) display a linear relation: a 1 mm distance error causes a 0.08 mm error of the evaluated radius.

As a consequence, an apparatus for *in vivo* measurements requires a measurement of the longitudinal cornea position. We suggest a system as displayed in Figure 4, with an auxiliary camera.

The best lateral cornea position can easily be found by the patient, by moving his head until a ring-shaped marker in front of the camera lens is centered with the (marked) camera lens.

3 Results

3.1 Bearing ball cornea dummy

A bearing ball dummy with a 7.500 mm radius was measured. The radius of the best-fit sphere from the evaluated data was found to be 7.5008 mm. (The bearing ball dummy under test belongs to the quality level G28 according to DIN 5401.) From the measured topography, a spherical surface with a 7.500 mm radius of curvature was subtracted. The difference is shown in Figure 5A. The deviation of the evaluated surface from the true surface varies between – 0.6 µm and 0.4 µm (see Figure 5B).

We note that this extremely good result is not statistically confirmed. Figure 5A displays a slight astigmatism. According to the quality level G28 of DIN 5401, the difference between the largest and smallest of the single diameters of a ball is smaller than 0.7 µm. It is not yet confirmed if this slight astigmatism demonstrates the real form of the bearing ball or just a measuring error, but the results just display that our method has the potential to be further developed.

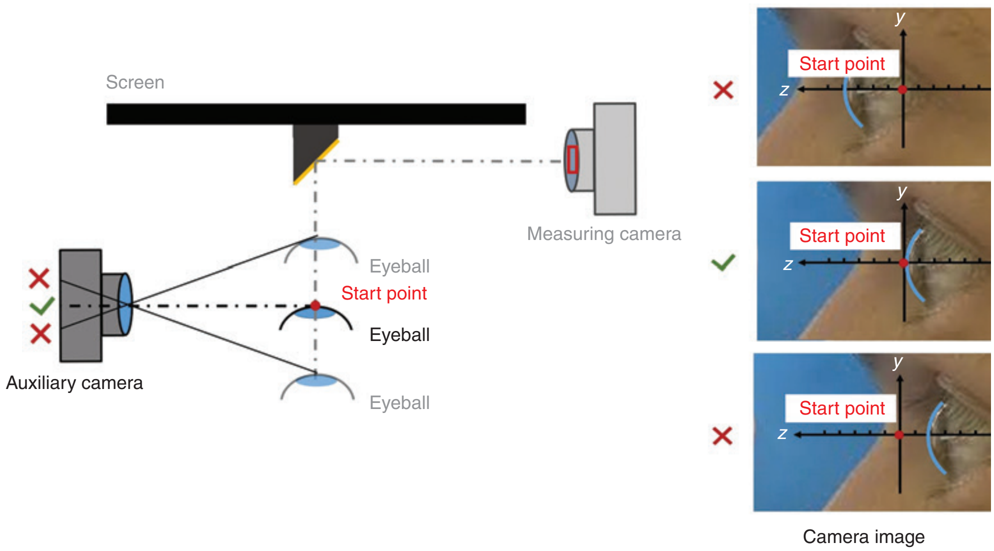

Figure 4: An auxiliary camera is suggested to measure the longitudinal cornea position.

3.2 Human eye *in vivo*

The data shown in the previous section were taken on a bearing ball cornea dummy. Handling of the human cornea is more difficult, due to possible motion blur by fast eye movements and by the low reflectivity of the cornea, as well as by parasitic reflections and scattering. Before the project started, it was an open question for us if the method would be applicable for the human eye.

It turns out that PMD can, indeed, measure the human cornea, as illustrated in Figure 6A. The camera image of the pattern reflected by the cornea displays a high contrast, with approximately constant fringe frequency. The small image at the right top corner displays the narrow band Fourier spectrum. This is an important intermediate result.

An *in vivo* test of the global trueness could not be achieved because the longitudinal position of the cornea as well as its shape is not exactly known, but the eye position can be estimated from the very small camera depth of field (±1 mm). Preliminary results in Figure 6 display the cornea shape, with a sag of 0.9 mm over a field of 7 mm. The difference of the measured shape versus a best-fit sphere (r = 7.85 mm) displays an astigmatism of 1.40 diopters. As explained, the global trueness of the *in vivo* measurement can only be estimated, but the measured astigmatic difference is quite encouraging: compared to the medical diagnosis of the test person (1.25 D astigmatism), the measurement deviates only by 0.15 D.

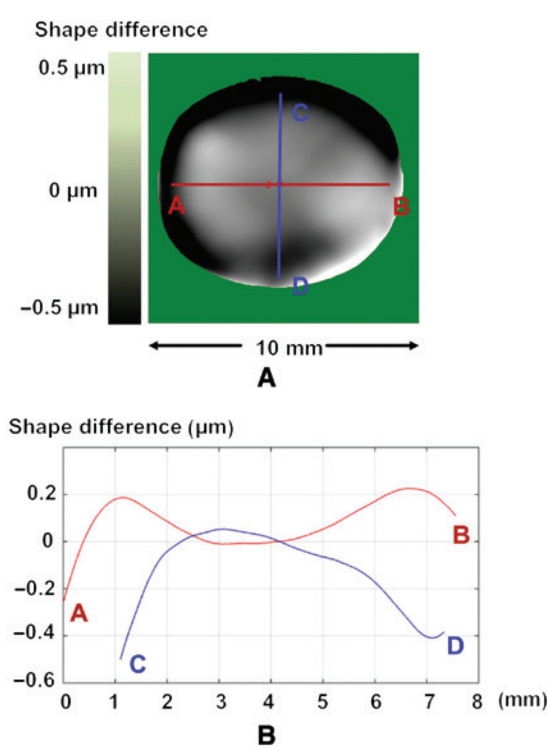

Figure 5: Bearing ball dummy, measured with PMD. Difference against nominal sphere (R = 7.5 mm). (A) Intensity encoded; (B) cross sections A–B, C–D.

4 Summary and conclusion

We implemented PMD to measure the human cornea *in vivo*. The method incorporates an optimized coaxial geometry adapted to the large slope range of the cornea (±29°) and measures a field of 7 mm, with a central obscuration

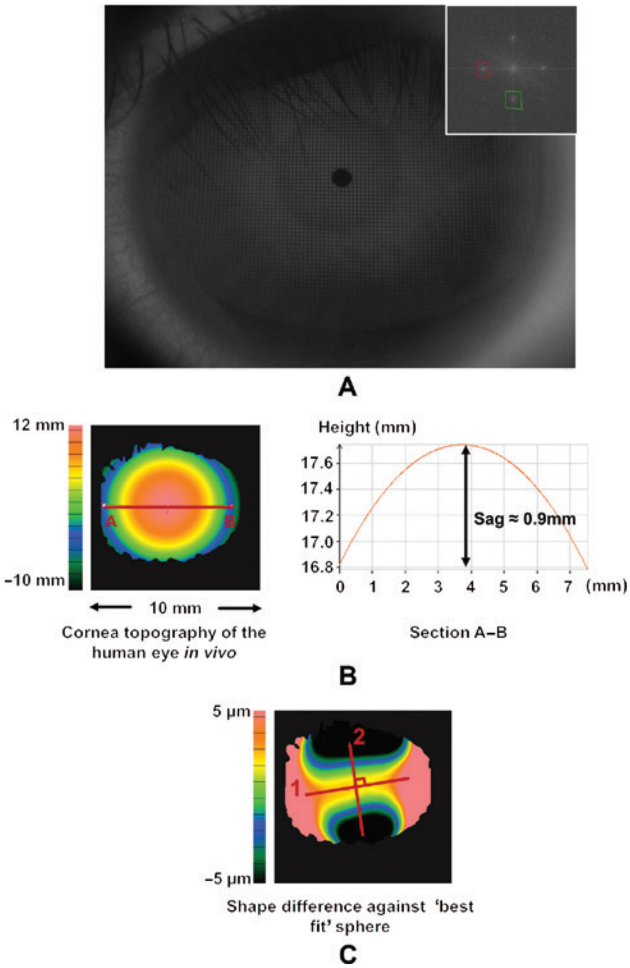

Figure 6: *In vivo* measurements of the human cornea. (A) Camera image and narrow-band Fourier spectrum top right, (B) cornea shape, (C) evaluation of the cornea astigmatism. From the measured radii R_1; R_2, the astigmatism is 1.4 D. The medical prescription for the test person's astigmatism is 1.25 (note that the prescription is in steps of 0.25 D).

of only 0.4 mm. It further incorporates a high lateral resolution exploiting the maximum possible fringe frequency of 12.5 periods/mm. The method exploits single sideband demodulation for single-shot phase evaluation. In spite of the low cornea reflectivity and parasitic reflections, clear images are acquired, to be accurately evaluated.

From measurements of a bearing ball dummy, we expect an achievable surface trueness in the range of a few micrometers or better. Accurate *in vivo* measurements require an accurate longitudinal positioning of the cornea. A method to measure the longitudinal position is suggested but not yet implemented. An *in vivo* measurement of a human cornea was performed, for a test person needing 1.25 D astigmatic correction. Our measurement with single-shot PMD displayed an astigmatism of 1.4 D.

References

[1] G. Haeusler, Pat. DE 19944354A1 (1999).
[2] B. Lingelbach and J. Massig, Pat. EP0924494 A3 (1999).
[3] J. H. Massig, E. Lingelbach and B. Lingelbach, Appl. Opt. 44, 2291–2287 (2005).
[4] Y. Mejia-Barbosa and D. Malacara-Hernandez, Optom. Vis. Sci. 78, 240–253 (2001).
[5] D. T. Puryayev and A. V. Laskin, Proc. SPIE 1877, 145 (1993).
[6] H. F. Holcomb, Pat. US4426141 A (1984).
[7] M. W. Belin and S. S. Khachikian, Clin. Experiment Ophthalmol. 37, 14–29 (2009).
[8] M. C. Knauer, J. Kaminski and G. Hausler, Proc. SPIE 5457, 366–376 (2004).
[9] S. Ettl, J. Kaminski, M. C. Knauer and G. Haeusler, Appl. Opt. 47, 2091–2097 (2008).
[10] C. Faber, E. Olesch, R. Krobot and G. Haeusler, Proc. SPIE 8493, 84930R (2012).
[11] H. Liang, Master thesis, Institute of Optics, University of Erlangen-Nuremberg (2016).
[12] Y. Liu, E. Olesch, Z. Yang and G. Haeusler, Adv. Opt. Technol. 3, 441–445 (2014).
[13] M. Takeda, H. Ina and S. Kobayashi, JOSA 72, 156–160 (1982).
[14] E. Olesch, C. Faber and G. Haeusler, Proc. DGaO 112, A3 (2011).

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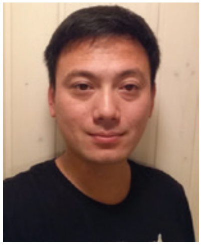

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