Creating patterns for phase shifting by rotation in deflectometry

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The deflectometric measurement of a specular surfaces depends on a unique coding of a screen pattern reflected in the surface. A robust and accurate method to create a unique coding is the usage of temporal phase shifting of fringe patterns with a cosine intensity modulation. As deflectometric measurements represent the surface gradients, these pattern sequences are usually shifted in two orthogonal directions on the screen. If for some reason a static screen pattern has to be used, the screen itself can be shifted in one direction, rotated by 90° and shifted in the other direction. Alternatively, together with a crossed fringe pattern with different periods in each direction, a phase shifting in only one direction is sufficient to obtain a coding in two orthogonal directions. For convex surfaces, where the size of the reflected fringes decreases with the distance from the center, this method has some disadvantages. Large fringe periods limit the phase shifting accuracy, but if the fringe period is chosen too small, the reflected fringes off the center can not be resolved any more. We propose a family of static patterns suitable for a rotational phase shifting that avoid this problem. The idea is to represent two crossed fringes in polar coordinates, i.e. as orthogonal counter-rotating spirals. Shifting these patterns in circular direction leads to a phase measurement of two orthogonal directions. These phase measurements are not given in Cartesian coordinates, so it is more complicated to evaluate them, but the phase sensitivity can be chosen within wide limits between radial and tangential direction.

1 Introduction

In ophthalmology, keratoscopes, see Fig. 1, are used to measure the shape of the cornea, e.g. to diagnose astigmatism. The basic principle is to view the image of the reflected concentric rings through a small hole in the center. If the cornea deviates from a circular shape, the reflection appears distorted.

Fig. 1 Keratoscope from 19th century for examining the anterior surface of the cornea [1]. It consists of a disk with concentric rings and hole in the center to view the reflection of the disk at the cornea surface.

Modern keratoscopes capture the reflected images and display the reconstructed shape deviations. This method has two drawbacks: First, the resolution of the surface normals is limited by the width of the rings. And second, deviations of the shape are only visible in radial direction as the pattern is constant in tangential direction.

The same measurement principle is used to inspect intraocular lenses, see Fig. 2. These lenses are used to replace or correct the eye's natural lens. Two reflections, one from the front and one from the back surface of the lens, interfere with each other, when patterns in the visible spectrum are used for inspection.

Fig. 2 Intraocular lens for treatment of cataract or myopia [2].

One way to prevent the back side reflection is to use UV light, which gets absorbed by the material (often PMMA). This prevents the usage of programmable display devices, instead static patterns have to be used.

In the next section briefly review a method to obtain a positional coding in two directions using a static pattern. Then we are introducing our method of patterns for rotational phase shifting.

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2 Related work

Liu et al. [3] describe a crossed fringe pattern, which shifted in one direction, leads to a phase measurement of two directions, see Fig. 3. The pattern as seen from the camera reflected at an convex glass surface is shown in Fig. 4.

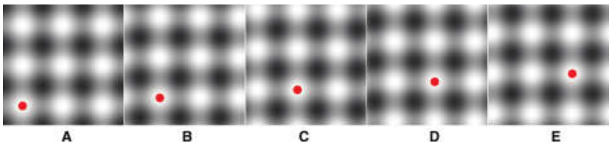

Fig. 3 *Temporal movement of the cross fringe pattern from Liu et al. [3] for five shifts.*

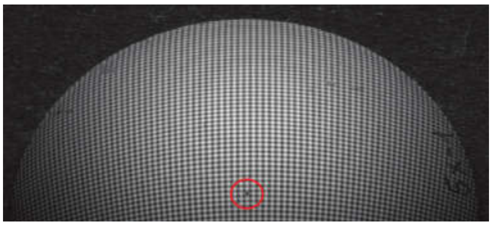

Fig. 4 *Cross fringe pattern from Liu et al. [3] reflected at convex eye-glass surface. The reflected fringes at the border of the surface are narrower and have lower contrast than in the center of the object.*

It can be seen, that contrast and period of the fringes decreases from the center to the border. This limits the choice of fringe patterns, because the fringe period has to be constant along the shifting direction.

3 Rotational phase shifting

The deflectometric measurement of a specular surfaces depends on a unique coding of a screen pattern reflected in the surface. A robust and accurate method to create a unique coding is the usage of temporal phase shifting of fringe patterns with a cosine intensity modulation. Let $I(r,\phi)$ be an intensity pattern in polar coordinates (radius r, polar angle ϕ) with gradient α, frequencies f_1, f_2, phase shift δ and mean value a and amplitude b_1, b_2:

$$I = a + b_1 \cos\left(\frac{f_1}{\alpha}\left((1-\alpha)\log(r) + \alpha(\phi+\delta)\right)\right) + b_2 \cos\left(\frac{f_2}{1-\alpha}\left(\alpha\log(r) - (1-\alpha)(\phi+\delta)\right)\right).$$

Fig. 5 *Two spirals with gradient $\alpha = 0.5$, frequency $f_1 = 5$ (left), $f_2 = 11$ (center) and sum of both spirals (right).*

An example of this pattern is shown in Fig 5. The gradient α changes the angle between both spirals, so it can be chosen between sensitivity in radial and tangential direction, see Fig. 6. An example of temporal phase shift is shown in Fig 7.

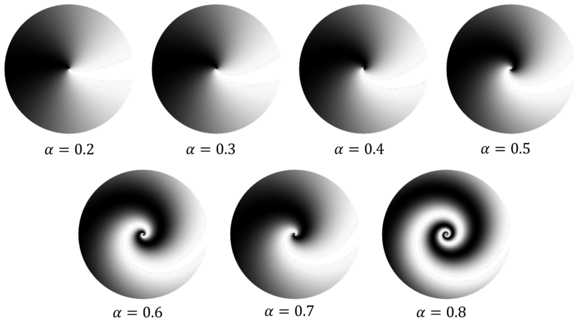

Fig. 6 *Varying gradient parameter $\alpha = 0.2\ldots0.8$.*

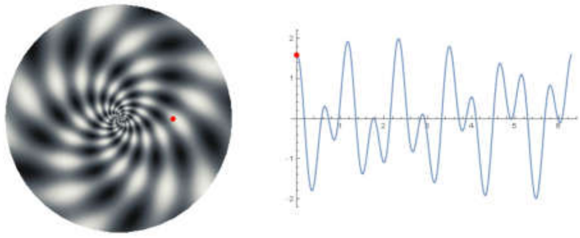

Fig. 7 *Spiral pattern (left) and time signal at one select point for $\delta = 0\ldots2\pi$ (right).*

Each spiral with gradient α can be presented in parametric form as follows:

$$r(\phi) = a e^{\tan(\alpha)\phi}.$$

The spiral is rotated via scaling the spiral with $a = e^{k2\pi}$, $k = 0,\ldots 1$.

4 Summary

We have presented a novel approach of static patterns for rotational phase shifting. The patterns are highly adoptable to specific tasks, i.e. the sensitivity in radial and tangential direction can be chosen in wide ranges.

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