Sub-micron profilometry on macroscopic free-form surfaces

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An important application of deflectometry is the measurement of local surface details that are only a few nanometers deep. However, it is difficult to detect these details in presence of big global height variations. We present a method for real-time reconstruction of height profiles from curvature maps to estimate the depth of sub-micron structures on free-form surfaces.

1 Introduction

One of the advantages of slope-measuring 3D sensor principles like Phase-measuring deflectometry (PMD) [1] is that one can achieve a tremendous dynamic range in terms of height variation with remarkably little technical effort. A typical PMD sensor setup for the measurement of eyeglass lenses has a local slope uncertainty of about 8 arcsec while being able to measure global tilts of $\pm 20°$. This corresponds to a dynamic range of approx. 18,000 : 1. By integrating slope data at a lateral sampling distance of 0.1 mm we get a local height uncertainty of only 4 nm, while still being able to measure objects with a global height range of about 10 mm. This corresponds to a dynamic range of approx. 2,500,000 : 1. This gain is achieved by virtue of numerical integration, which is an operation that emphasizes low-frequency shape information and reduces high-frequency noise.

In recent publications [2, 3], we presented techniques to reconstruct the shape of an object from the measured slope data with high accuracy. We demonstrated that using these techniques it is possible to preserve small details like scratches or grooves on macroscopic free-form surfaces that are only a few nanometers deep [3]. However, for evaluating the depth of these structures on non-flat surfaces, the reconstructed height map is of little use: The global height of the object typically exceeds the depth of the structures by several orders of magnitude. To make the structures visible, one has to *separate* them from the global object shape. A straightforward way to do this would be to subtract the global shape. This method assumes that the shape is known in advance, e. g., as a CAD model, and the measured surface exactly realizes this model. Furthermore, the surface and the model need to be aligned to each other with sufficient precision. For smooth surfaces, this is a difficult task by itself [4]. Typically, the errors caused by inaccurate sensor calibration, manufacturing, and misalignment are in the range of several microns. This is still much larger than the size of the structures we want to detect.

Another way to separate the details from the global shape is high-pass filtering. This is a common method for *edge detection* in image processing. By applying a Laplacian filter, for instance, the coarse object shape can be suppressed sufficiently to detect the desired microstructure. The Laplace operator, which is a numerical differentiator, reduces the dynamic range to approx. 600 : 1. However, these filters usually do not retain enough geometric information to reconstruct the depth of the visible structures from the filtered result.

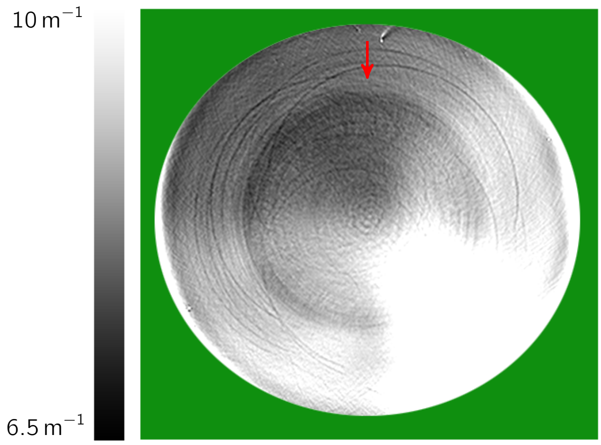

Fig. 1 *Mean curvature of a progressive eyeglass lens, displaying milling grooves. Marked in red is a cross-section of 6 mm length (see Fig. 2).*

2 Curvature Maps

For a slope-measuring sensor principle like PMD it is advantageous to differentiate the slope data just once instead of differentiating the height map twice (by applying the Laplace filter). To preserve the complete geometric information that is necessary to quantify the microstructure, we calculate the *curva-*

ture map of the surface.

The curvature map is a tensor field, specifying for each surface point a symmetric 2×2 matrix that is known as *Weingarten matrix* or *shape operator*. The theorem of Bonnet states that it is possible to uniquely reconstruct the object's shape from this tensor field [5]. The eigenvalues κ_1 and κ_2 of the shape operator are the *principal curvatures* of the surface. Fig. 1 depicts the mean curvature $(\kappa_1 + \kappa_2)/2$ of a progressive eyeglass lens as a gray scale image. The microstructure of the surface—scratches and milling grooves—are clearly visible in this representation. We now describe a method to estimate the depth of these structures.

3 Reconstruction

For this task, we restrict ourselves to reconstruct only a *height profile* instead of a full 3D representation of the microstructure. This has the advantage that we do not need to deal with non-integrable 2D vector fields (see [3]). We choose a cross-section in the mean curvature map (see Fig. 1) and take samples of the *normal curvature* κ_n along this cross-section. It is calculated by Euler's formula

$$\kappa_n(\beta) = \kappa_1 \cos^2\beta + \kappa_2 \sin^2\beta\,, \qquad (1)$$

where β is the angle between the direction of the cross-section and the first principal curvature direction.

If the cross-section is small enough, the basic shape can be assumed to be spherical, thus yielding only a curvature bias. We remove the curvature bias by subtracting the sample mean. The resulting curvature section is depicted in Fig. 2.

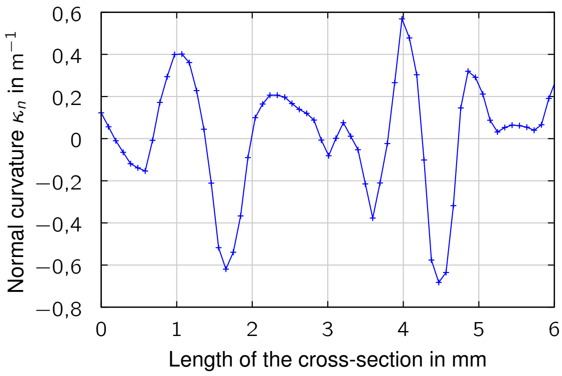

Fig. 2: Normal curvature along the cross-section marked in Fig. 1. The curvature bias has already been removed.

From differential geometry we know that it is possible to uniquely reconstruct the shape of a planar curve only from its curvature up to translation and rotation [5]. This can be done by solving the differential equation

$$f''(x) - \kappa_n(x)[1 + f'(x)^2]^{3/2} = 0 \qquad (2)$$

to obtain the desired height profile $f(x)$. We solve (2) by employing a 4$^{\text{th}}$-order Runge-Kutta integration scheme.

4 Results

The reconstructed height profile is depicted in Fig. 3. From this we can conclude that the two main grooves along the cross-section are about 60 nm and 35 nm deep, respectively. Experiments have shown that the accuracy of the reconstructed profile mainly depends on the sampling distance of the curvature values. This is caused by the error propagation introduced by the numerical integration method. Therefore, we should only consider small, densely sampled cross-sections. In case of aspherical surfaces, this also helps to remove the curvature bias, which can be assumed to be constant.

Since the cross-section consists only of a small number of data values, the reconstruction can be done in real-time, allowing the user to examine the microstructure of a surface as in Fig. 1 interactively.

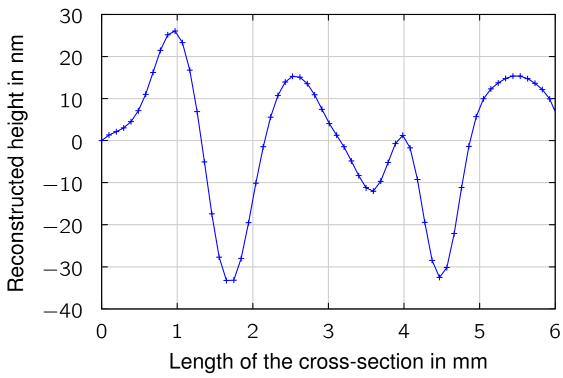

Fig. 3: Height profile of the reconstructed grooves.

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