Non-stereoscopic Method for Deflectometric Measurement of Reflecting Surfaces

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General deflectometric methods are subject to an ambiguity regarding the determination of the surface normals. A typical way to resolve this is to use two cameras (Stereo Deflectometry [1]). Here we present a deflectometric method, which uses only one camera image and a priori information about the surface.

1 Introduction

With deflectometric methods a known pattern is observed in reflection of a specular surface whose height distribution is to be measured.

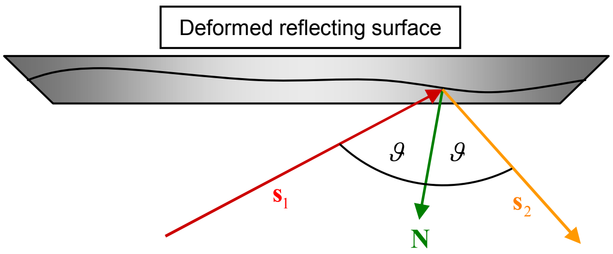

Fig. 1 *Principle of deflectometric measurement*

If the light ray $\mathbf{s}_1$ from the pattern and the light ray $\mathbf{s}_2$ to the observation are known (Fig. 1), the normal at the incident point (x,y) can be calculated by:

$$\mathbf{N}(x,y)=\frac{\mathbf{s}_2-\mathbf{s}_1}{|\mathbf{s}_2-\mathbf{s}_1|} \tag{1}$$

To obtain a height distribution, gradients are required which are determined from the normals by:

$$\vec{\nabla}h(x,y)=-\frac{1}{Nz(x,y)}\begin{pmatrix}Nx(x,y)\\ Ny(x,y)\end{pmatrix} \tag{2}$$

The height distribution $h(x,y)$ is then computed by integrating the gradients.

2 Ambiguity of Normal Determination

General deflectometric methods which use a scattering pattern are subject to an ambiguity regarding the determination of the surface normals.

Assuming that the position of one point in the pattern is found in the sensor plane, the corresponding camera ray can directly be calculated. Back tracing this ray yields many possible surfaces – and therefore normals – which reflect the pattern point into the camera (Fig. 2).

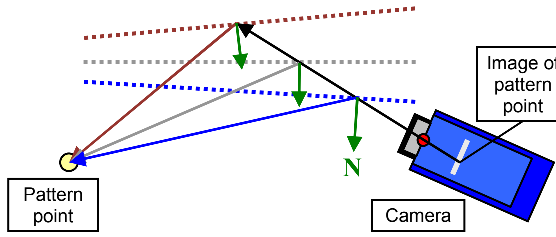

Fig. 2 *Back traced pattern point with three possible surfaces and their related normals*

Existing approaches to resolve this ambiguity include the use of a stereoscopic setup with two cameras (Stereo Deflectometry [1]) and the use of direct coding of the illumination direction together with a telecentric observation (RCD [2]).

The approach which is presented here uses a priori information about the surface and an iterative algorithm to resolve the ambiguity.

3 Non-stereoscopic Surface Reconstruction

It is assumed that the surface has a smooth height distribution without discontinuities and that its borders lie on a holding frame (Fig. 3).

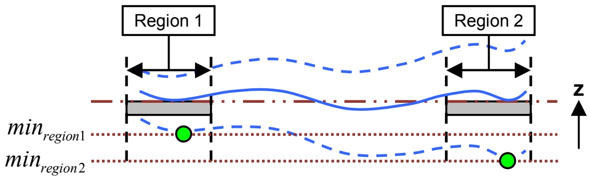

Fig. 3 *Original surface lying on a frame and two reconstructed surfaces with wrong start heights*

A self-consistent iterative method is used to reconstruct a surface corresponding to a given start height [3]. The height values are approximated from the gradient data by shifted base functions [4].

The first reconstruction is done with an arbitrary start height. If the start height does not match the correct one the reconstructed surface shows a slight deformation and – important here – a characteristic tilt (Fig. 3).

The tilt is visible in the difference between the minima in the surface's frame regions:

$$\Delta h_{\min} = \min_{region1} - \min_{region2} \qquad (3)$$

If the absolute value of $\Delta h_{\min}$ is equal or below a given threshold, the algorithm stops and the height distribution of the measured surface is obtained with high accuracy.

In the other case, the sign of $\Delta h_{\min}$ defines the direction in which the start height has to be altered. If $\Delta h_{\min}$ is positive, the start height has to be increased, if $\Delta h_{\min}$ is negative the start height has to be decreased. The step size is diminished, if a change in the direction occurs. Then another reconstruction with the new value is performed (Fig. 4).

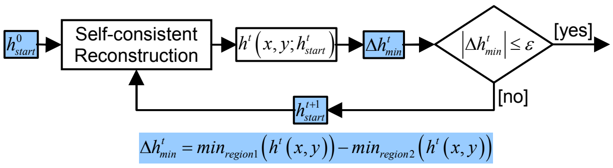

Fig. 4 *Finding the best start height*

4 Simulation

In this simulation, a test surface is used which has a size of 25.4 mm in x-direction, 57.15 mm in y-direction and a height range of 40 µm (Fig. 5). The pattern consists of discrete round-shaped markers with a gradient profile.

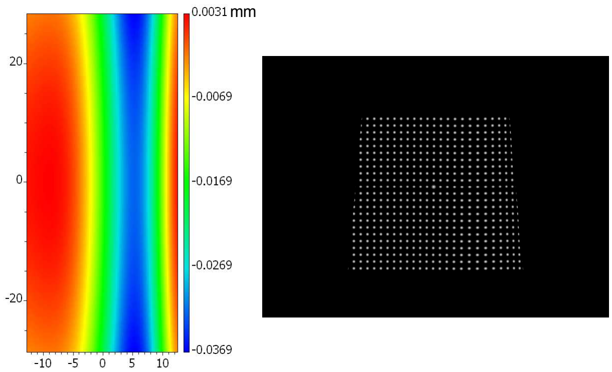

Fig. 5 *Simulated height distribution and the corresponding camera image (1360 x 1024 px)*

With a given limit of 0.1 µm for $|\Delta h_{\min}|$, the algorithm converges after six start height variations whereas between three and five self-consistent reconstructions are needed at each start height. The resulting start height is -12.5 µm and the computation time is below one minute.

The maximum error of the reconstructed height distribution is 0.4 µm, in the region of interest between the frame regions 0.3 µm (Fig. 6).

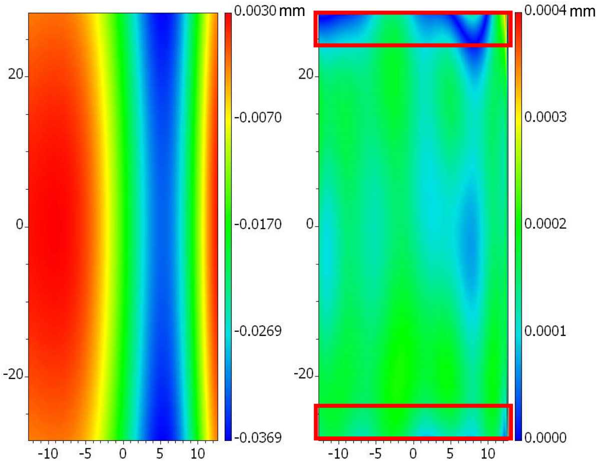

Fig. 6 *Reconstructed height distribution and absolute value of the difference between reconstructed and simulated height distribution (red boxes: frame regions)*

The error originates from three sources: The approximation errors produced by the shifted base functions, the lack of gradient data in the frame regions and the inaccuracy in the determination of the markers' positions in the camera image.

5 Application

This approach is used to eliminate the time consuming focus search in systems biology, where a lot of individual experiments on one thin and therefore deformed glass substrate are observed by microscopy.

6 Conclusion

If a priori information about the surface is available, the ambiguity regarding the determination of the surface normals can be resolved by using an iterative algorithm. The height distribution is reconstructed with an accuracy below 1 µm.

References

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