INSPECTION OF REFLECTIVE SURFACES WITH DEFLECTOMETRY

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SUMMARY: Phase-measuring deflectometry combines the advantages of fringe-phase measurement, with sensitivity about 1/1000th fringe of displacement, and surface-slope measurement, with sensitivity especially to small-scale surface disturbances. As opposed to fringe-projection techniques (which rely on surface scattering), deflectometry requires specular reflections. An overview is given of deflectometric signal capture and processing strategies developed in recent years in the "Image-based Measurement Systems" workgroup at the Fraunhofer IOSB.

INTRODUCTION

The general experimental set-up for phase-measuring deflectometry [1-3] is shown in Figure 1. A reference screen, typically a flat-panel computer or TV monitor, is used to display a sequence of fringe patterns, whose reflection from the surface under test is captured by one or more camera sensors. The pattern coding sequence is such that each screen co-ordinate (u,v) is uniquely identifiable in the patterns recorded at each pixel (x,y) on the camera sensor; typically, several phase-shifted sets of fringe patterns of different widths are used [4]. Deformations of the observed fringe patterns, imparted by the shape of the tested surface, can be exploited for analysis of its properties. It is important to realise that the fringe-displacement signal encodes the slopes of the surface, not its co-ordinates; consequently, surface reconstruction requires integration of both partial derivatives/slope signals with adequate mathematical methods [5, 6].

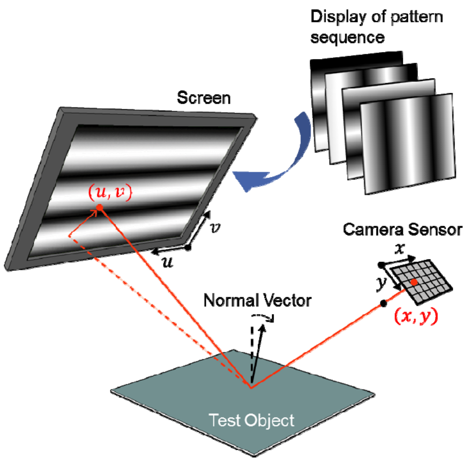

FIGURE 1: Deflectometric measurement system. The patterns displayed on the screen are reflected by the test object and recorded by the camera sensor.

For a *measurement*, i.e. a metric evaluation of the data and a correct conversion of the observed fringe displacements into a field of surface normal vectors, the geometric parameters of the system need to be known very accurately. This includes the focal length of the imaging lens and its distortions, and the relative locations in space between screen, sensor, and at least one point of the object surface.

For an *inspection* or test, approximate knowledge of the geometry parameters is sufficient, especially when local defects are the features of interest. This is a common task in applications, as the local gradients and curvatures of a surface are very relevant for the cosmetic appearance of a surface and hence, its aesthetic value. Since deflectometry is a gradient technique, it is exquisitely sensitive to local features.

TECHNIQUES OF SURFACE INSPECTION

There are several ways to evaluate fringe patterns from an uncalibrated measurement system; the first of these is simply local fringe density, shown in Figure 2. In this simplest of implementations, the local variation in fringe density is taken as a relative error measure. Conceptually, this is even possible with one fringe pattern per spatial direction.

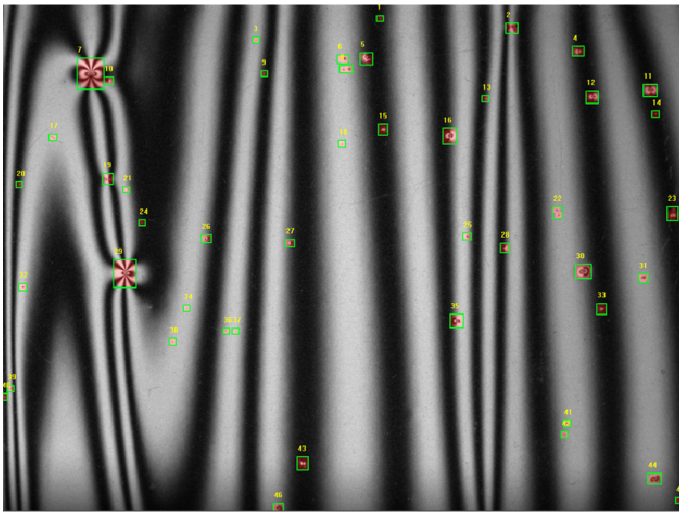

FIGURE 2: Deflectometric fringe pattern as recorded by camera, with local surface flaws automatically detected and labelled.

If a full set of phase-shifted fringe images is available, phase maps can be calculated and evaluated for local curvature deviations. Note that the calculation of curvature requires a differentiation of the surface slopes. In principle, this, too, requires the exact field of surface normals; but the process of differentiation is far less sensitive to calibration uncertainties than the surface reconstruction procedure, where any errors are magnified and propagated through the 2-D integration of the slopes. Figure 3 presents a simplified flow diagram of local curvature assessment.

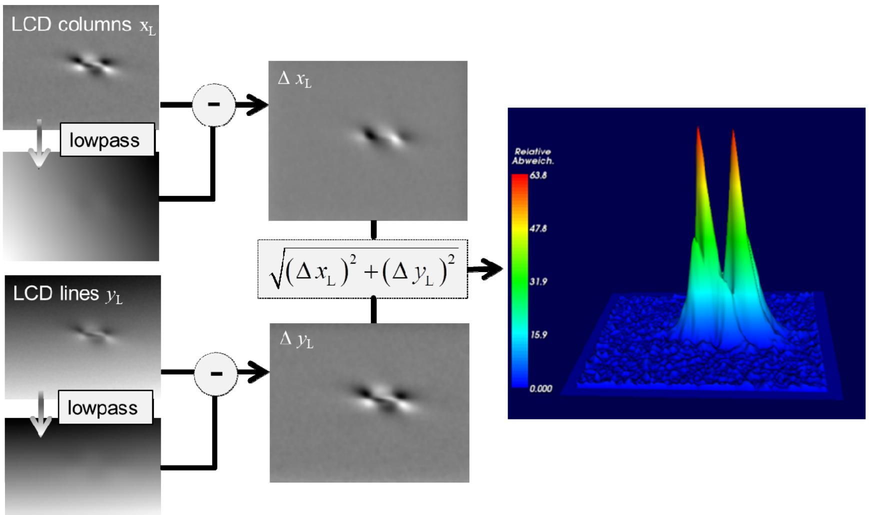

FIGURE 3: Using local curvatures to detect defects. Curvature maps for the two spatial directions are stripped of their global components (which, on curved surfaces, would drown out small local signals), combined into the averaged curvature and displayed on a relative error scale.

Curvature analysis is not only useful for detecting local defects, but also for quantitative analysis of surface quality, as is often required in production monitoring. One such example is the analysis of paint systems, where “orange peel” (a slight ripple in the finished paint) sometimes is introduced deliberately to mask small scratches or dents in the painted substrate (where a couple of µm of depth are readily detectable by human observers and are perceived as cosmetic flaws), and sometimes is to be avoided as much as possible. Deflectometric sensing of this and other surface parameters allows reproducible monitoring and documentation of production results, which is a prerequisite for systematic improvements of production processes. Figure 4 shows examples of orange-peel analysis.

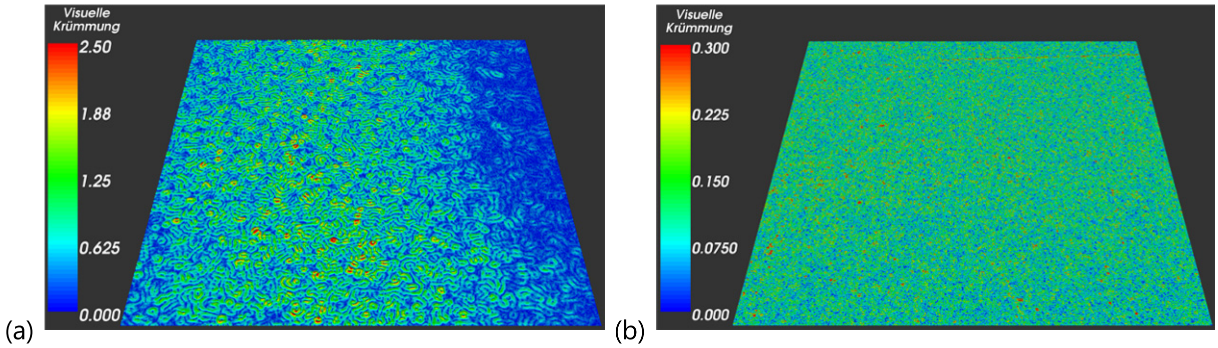

FIGURE 4: Orange-peel analyses. (a) Distinct orange peel; curvatures up to 2.5/m (i.e. local radii of curvature down to 400 mm); (b) no perceptible orange peel even at 0.3/m (radii of curvature of 3300 mm).

INFRARED DEFLECTOMETRY

The previous example mentioned the occasional necessity to cover up minor surface defects by orange peel. Not surprisingly, manufacturers are also looking for ways to recognize defects on raw or primed parts before they are revealed (too late) by the final layer of glossy paint. It turns out that this cannot be done with fringe projection: whilst it works extremely well with scattering surfaces and generates 3-D data directly, it is not sufficiently sensitive on the µm scale. A new approach developed at the Fraunhofer IOSB is deflectometry at infrared wavelengths, where many surfaces are still reflective that are already scattering in the visible. Note that there is no immediate penalty for using a much longer wavelength as the law of reflection still applies; hardware and implementation are more demanding however. Figure 5 presents the salient features of infrared deflectometry. Different ways have been explored to provide IR fringe patterns [8]; shown here is a very robust technique that lends itself well to scanning techniques and/or inspection of moving parts.

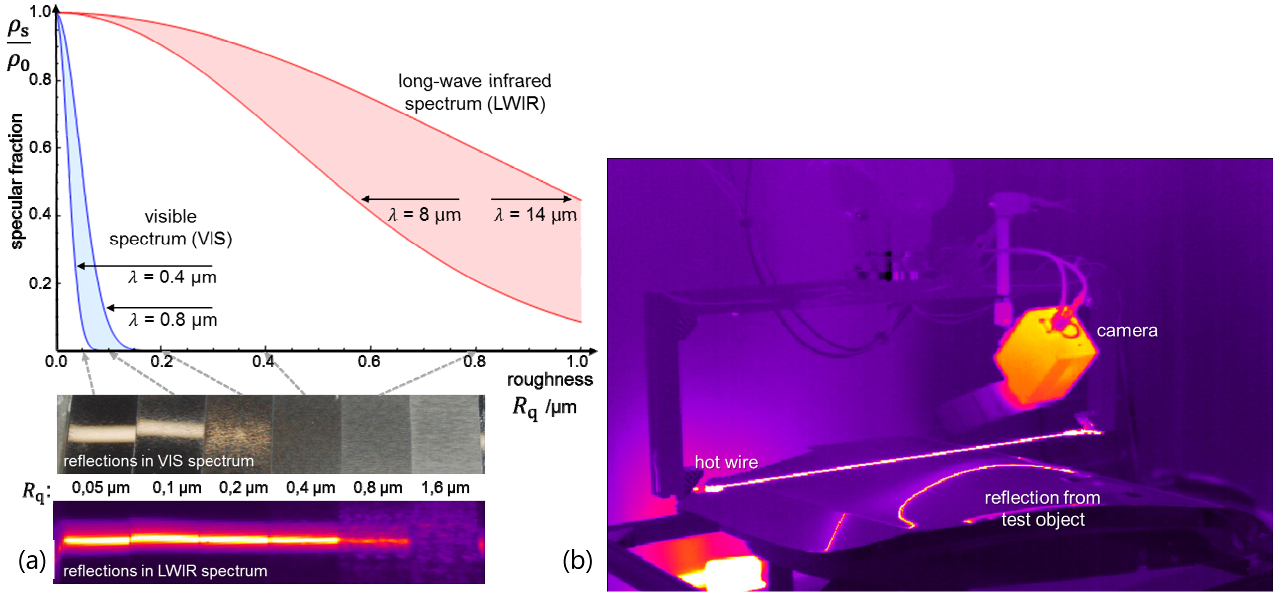

FIGURE 5: IR deflectometry (a) diagram of specular vs. diffuse fraction for different wavelengths, and experimental images of reflections for different surface roughness readings; (b) laboratory system, where the IR emission is provided by a single hot wire.

In general, almost all technical surfaces are neither perfectly scattering nor perfectly specular, and it can sometimes become difficult to decide whether to use fringe projection or deflectometry for best results. IR deflectometry significantly extends the practitioner's freedom in that regard.

PHOTOMETRIC STEREO

Another way to bridge the gap between reflective and diffuse surfaces is the photometric stereo technique, using several light sources at shallow angles of incidence and comparing the resulting intensity maps. This technique is suitable for measuring local surface slope and reflectance on slightly to completely diffuse surfaces, and preliminary findings indicate that the sensitivity to surface defects is similar to that of deflectometry [9]. Figure 6 shows the experimental set-up and some results.

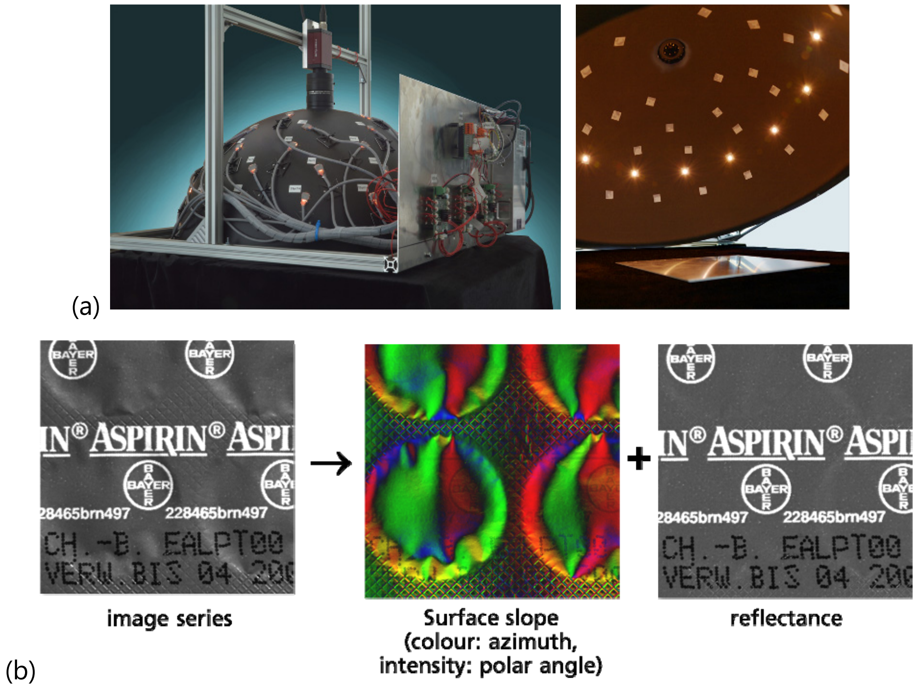

FIGURE 6: (a) Experimental photometric stereo set-up: dome with LEDs at different azimuthal and polar angles, and camera on top, observing object at nominally normal incidence. (b) Example of image analysis. A series of images is analysed for surface normal vectors and reflectance.

CONCLUSION

Deflectometry is an important part of the surface inspector's toolkit; besides its capability to measure aspherical and freeform surfaces at high dynamic range with very simple means, it also lends itself well to tasks of local defect detection thanks to its sensitivity afforded by the inherent gradient measurement. Its applicability and sensitivity can be extended to rougher surfaces by using infrared radiation, and reproduced through scattered-light analysis in the photometric stereo technique.

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