

Suppression of contrast-related artefacts in phase-measuring structured light techniques

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In fringe-projection and deflectometric measurements that use structured illumination, measurement artefacts can be observed around abrupt changes of surface reflectivity. This can lead to incorrect error classification. We explore the origin of the phenomenon by simulation and modelling, and offer a first attempt at correcting these errors.

1 Introduction

Phase shifting [1] is by far the most successful structured-light method when low uncertainty is desired. When temporal phase shifting is used, each camera pixel theoretically functions as an independent phase-measuring device, achieving uncertainties of hundredths of a fringe quite easily. However, this is no longer valid when the tested surface shows sharp changes in reflectivity that the optical system cannot resolve, as Fig. 1 shows.

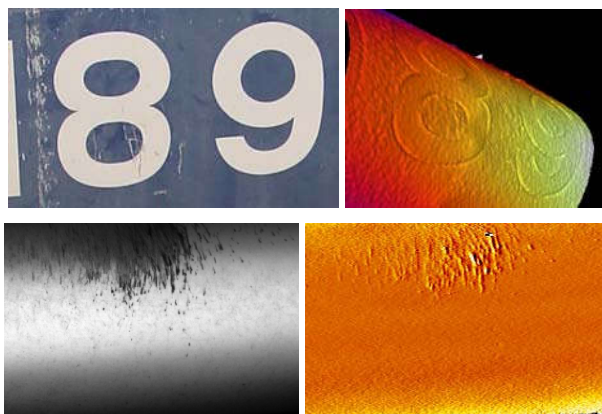


Fig. 1 Top row: left, textured panel; right: 3-D data from fringe-projection measurement. Bottom row: left, polished metal surface with contamination; right: map of horizontal slopes from deflectometric measurement.

It is quite clear from these examples that reflectivity changes create phase artefacts, typically in the form of over-/undershoots. In fringe projection, this creates implausible surface features; in deflectometry, bogus curvature defects appear that cannot be distinguished from reflectivity defects.

The problem is well known to all practitioners, but until very recently [2],[3], no studies of it were documented; hence we offer this attempt at understanding and compensating this type of errors.

2 Simulation

We define a 2-D reflectivity distribution on a 256x256 pixel raster and then model its blurring by simple 2x2 binning of pixels, so that a new image of 128x128 pixels results. Fig. 2 shows the process. Note that structured-light techniques always use fringe patterns of some spatial period p , which is then temporally shifted; hence we are dealing with a spatio-temporal phase measuring method.

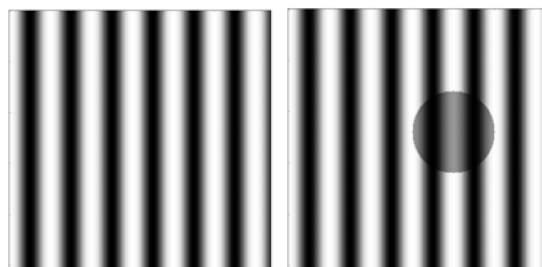


Fig. 2 Left: unperturbed fringe pattern; right: perturbed fringe pattern with no changes in phase but a hard edge defined by lower fringe modulation M . The 2-D data layout is not strictly necessary, but allows the investigation of slanted edges as well.

The phase data are then computed from a sequence of simulated phase-shifted images with a simple 4-step 90° phase-shift formula, and the phase errors are determined by subtracting the reference data. Fig. 3 shows the errors found. Clearly, the under-/overshoot behaviour found in practice is reproduced.

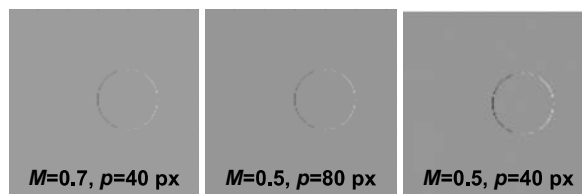


Fig. 3 Relative phase errors in response to M and p , displayed in equal grey scales.

3 Theory

We investigate the measured and averaged intensities by the example of a vertical edge as in Fig. 4, where j is the column index. Since we are dealing with a vertical fringe pattern in the example, only changes in horizontal direction are relevant.

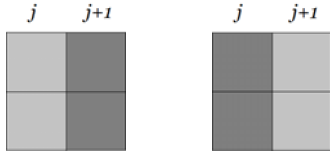


Fig. 4 Case analysis for reflectivity step, high to low (left) and low to high (right).

For the case illustrated on the left in Fig. 4, i.e. a sudden drop of M , we have

$$\begin{aligned} I(i, j) &= I_H + M_H \cos\left(\frac{2\pi}{p} j\right) \\ I(i, j+1) &= I_L + M_L \cos\left(\frac{2\pi}{p} (j+1)\right), \end{aligned} \quad (1)$$

where subscript H stands for the higher and L for the lower modulation. Combining four measurements in a 2x2-pixel bin gives

$$\phi_M = \frac{4\pi}{p} j' + \arctan \frac{\sin \frac{2\pi}{p}}{2M_H + \cos \frac{2\pi}{p}}, \quad (2)$$

as opposed to

$$\phi_M = \frac{4\pi}{p} j' + \frac{\pi}{p} \quad (3)$$

for the unperturbed case; the j' are the new column indices after binning. For slanted edges, Eq. (2) will of course look different; regardless of the geometry, the quotient in the arctan expression is always $\Sigma M_j / \Sigma M_{j+1}$. The difference of Eqs. (2) and (3) is the phase error $\Delta\phi$ (the reader may wish to check that $\Delta\phi = 0$ for $M_H = M_L$). So, the error depends on the ratio of high and low modulations found, and on the fringe period. A modulation map is a by-product of all phase-shifting calculations; but the error correction also relies on a good estimate of the local fringe density, which is not that easy to obtain when the object imparts strong distortions to the fringe pattern.

4 Practical test

We tried various ways to apply the correction terms to actual measured phase maps, with different columns being inserted for computing the compensation terms. It turned out that an indiscriminate correction of the entire image did not lead to significant improvement; the reasons for

this are not yet clear. Better success was achieved by pre-processing the modulation maps with a Sobel filter; some results from the best method found so far are shown in Fig. 5.

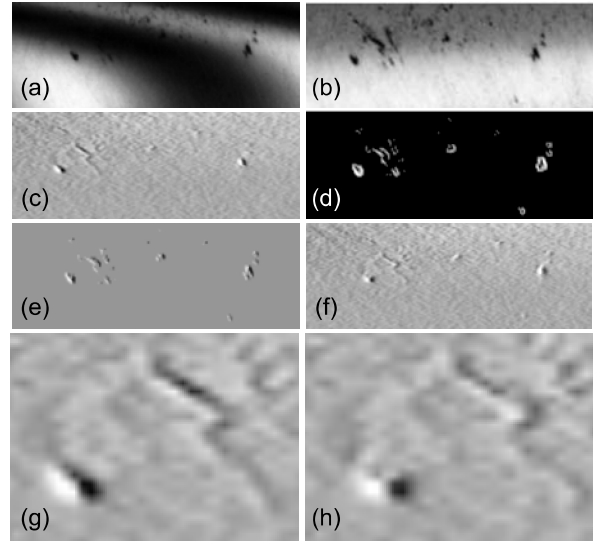


Fig. 5 Test of correction with real data. (a) fringe image; (b) modulation map; (c) uncorrected phase map; (d) edge pixels detected with Sobel filter; (e) corrections computed; (f) corrected phase map; (g) close-up of uncorrected phases; (h) same region after correction.

As can be seen, the compensation is nowhere near perfect, which suggests that the effects modelled and compensated are only a partial description of the actual behaviour.

5 Conclusions

The error correction derived does not suppress modulation-induced phase artefacts well enough yet; more research with real data is needed to understand the error generation mechanisms more completely. One intrinsic difficulty is given by the varying fringe densities, and possibly also the fringe directions. In deflectometry, where slopes are being measured, it may also be possible to rule out some artefacts because the slope maps would lead to implausible topographic data.

References

- [1] J. Burke: "Phase Decoding and Reconstruction" in *Optical Methods for Solid Mechanics: A Full-Field Approach*, P. Rastogi, E. Hack (eds.) (Wiley, 2012), pp. 83-141
- [2] Y. Wu, H. Dantanarayana, H. Yue, J. Huntley: „Accurate characterisation of hole geometries by fringe projection profilometry“ in *Videometrics, Range Imaging, and Applications XIV*, Proc. SPIE 10332 (2017), pp. 1033204-1033204-7
- [3] J. Burke, L. Zhong: „Suppression of contrast-related artefacts in phase-measuring structured light techniques“, in *Optical Measurement Systems for Industrial Inspection X*, Proc. SPIE 10329 (2017), pp. 103290T-103290T-12