Deflectometric Self-Calibration for arbitrary specular surfaces

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Phase Measuring Deflectometry (PMD) is a well established method to precisely measure the local slope of specular surfaces. To acquire the global shape, the slope data has to be integrated, a procedure known to be very sensitive to systematic errors. Therefore an extremely accurate calibration of the sensor is necessary. To obtain this, a new self-calibration method was developed.

1 Introduction

To measure specular surfaces our group developed the Phase Measuring Deflectometry (PMD) in the year 1999 [1]. Meanwhile the sensor is well established in the industry to control the manufacturing of eyeglasses. For this application the surface refractive power is needed. The primary measurand of the sensor are the slopes. So, only one derivation is needed to calculate the curvature. The accuracy of that calculated curvature is 1/100 dpt. There is a considerable interest in industry to use PMD also for height measurements to replace the time consuming coordinate measuring machine. Why hasn't this been done already? To calculate the height data, the measured slopes have to be integrated [2]. Every integration method is very sensitive to systematic errors. Therefore, the global accuracy on a field of 80 mm x80 mm is typically only about 3 µm due to the calibration errors.

2 Calibration Parameters

During the measurement, a camera observes a sinusoidal pattern. To reconstruct the object under test, the reflection direction of the observing camera ray must be calculated for each single pixel. For this step a lot of parameters have to be known, i.e. calibrated for each single system.

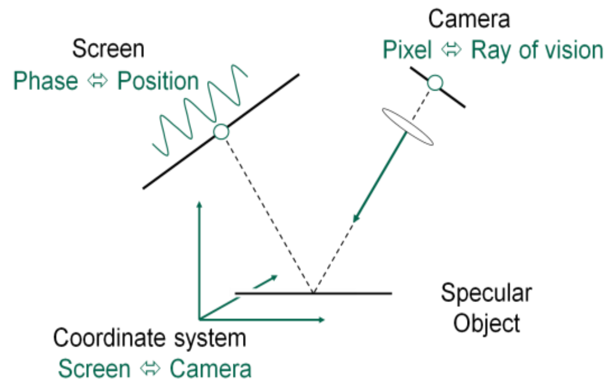

Fig. 1 *Calibration overview*

Fig. 1 shows an overview of the required calibration parameters. First: the pattern on the screen. The result of the evaluation algorithm is the phase of the observed sinusoidal pattern. This phase has to be related to a position on the screen. The next step is the internal camera calibration. Here every pixel of the camera is related to the direction of a ray of vision. In the last step, both results have to be put in one coordinate system.

3 Common Calibration Method

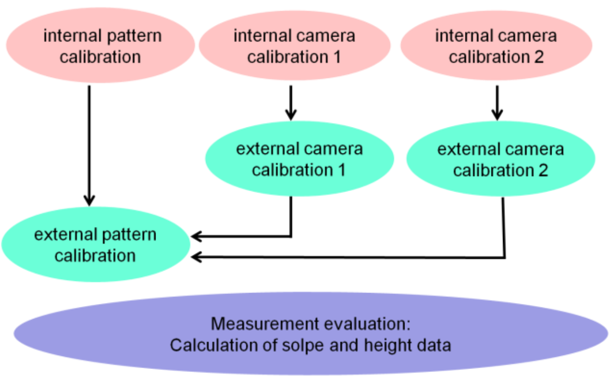

Fig. 2 *Stepwise calibration method*

The common calibration makes use of an optimization algorithm well known from photogrammetry, the so called bundle adjustment. For this reason it was necessary to decompose the calibration into several isolated steps (fig. 2). Every step has to deal with noisy data and with the inaccurate result of the previous step. This inconsistency in combination with the associated error propagation results in large systematic deviations for the calibration parameters. Unfortunately, the evaluation resp. data processing required for the actual measurement (reconstruction of slope data and calculation height data by integration) is very sensitive to these systematic errors.

4 New Self-Calibration Method

To improve the global accuracy, a new calibration method is required. The best results are expected from a holistic method, which calculates all the calibration parameters in one Algorithm. Inspired from the idea of the bundle adjustment as an iterative self-consistency approach, we developed a self calibration method for deflectometric sensors for arbitrary specular surfaces. It's a further development of the calibration method we presented last year [3]. There the measurement of a planar mirror in several tilted positions was required to calculate all the sensor parameters. Now the calibration is expanded to arbitrary specular surfaces. It is not necessary to know the object form, this is even a result of the calibration algorithm. The general calibration is an iteration of 3 different steps (fig 3). In the special case where the shape of the (curved) object used for calibration is known in advance (e.g. a precision sphere), only the first step with only one measurement is needed, already providing sufficient data to determine the calibration parameters. Otherwise measurements of several tilted object positions are needed.

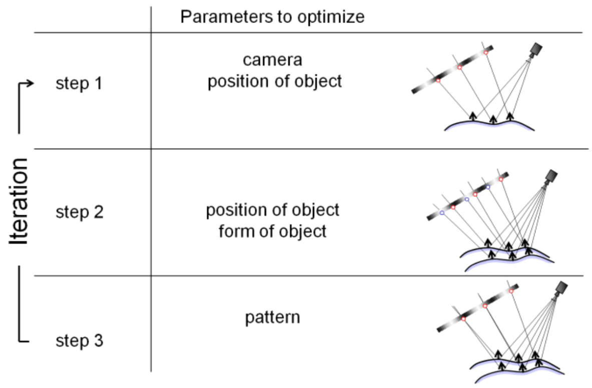

Fig. 3 *New Self-Calibration Method*

In the following the different iteration steps of the new self-calibration method are described:

<u>*Step 1:*</u> Here the camera(s) (internal and external) and the position of the object are optimized under the (current) assumption of a given object form. This is possible because the form and the position of the object influences the direction of the reflected ray of vision of the camera, although the specular object itself is "invisible".

<u>*Step 2:*</u> Now the camera parameters are fixed and the object form and positions are recalculated. Similar to the stereo approach, the algorithm searches the object form and the according normals which explain the measurement results best.

<u>*Step 3:*</u> The last step is the calibration of the pattern. The camera parameters and the object form and positions are fixed. By triangulation of the reflected rays of vision of the camera, the pattern can be recalculated.

This procedure is iterated, until the desired accuracy has been reached.

5 Experimental results

We measured a planar mirror (surface flatness λ/10). First we calculated the height result of the measurement with calibration parameters determined by the common calibration method (fig 4 left). On a field of 80 mm x 80 mm the global accuracy is about 3 µm. Then we evaluated the same measurement with calibration parameters which have been calculated with the new self-calibration method. The global error on the same field is here reduced below 1 µm (fig. 4 right). Nearly no systematic error can be seen. The remaining error is the subject of further study.

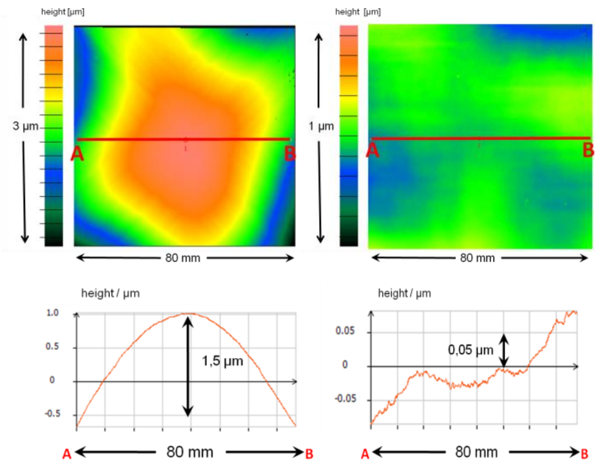

Fig. 4 *Measurement of a planar mirror: height results on a field of 80 mm x 80 mm. Left: Sensor calibrated with the common calibration method. The global accuracy of the height result is about 3 µm. Right: Sensor calibrated with the new self-Calibration method. The global error is reduced to about 0.5 µm.*

6 Conclusion

The global accuracy of reconstructed height data from a PMD measurement is very sensible to systematic errors. Therefore the calibration of the sensor geometry is essential. To improve the calibration we developed a new global self-calibration method. With this method the global accuracy on a field of 80 mm x 80 mm is reduced from 3 µm under 1 µm

References

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