Evaluating the limits of a focus based depth measurement system

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Abstract

This paper deals with an experimental accuracy evaluation of an optical, focus based depth measurement system. For inspecting micro-components in-place, the system can easily be integrated into a production system. It reconstructs the reference object's three dimensional surface. For the experimental accuracy evaluation a micro stair reference object is used. The height of each step is calculated by fitting planes into the reconstructed surfaces. Reproducibility of the system is analysed by repeating the surface reconstruction of a reference object N times. Standard deviation for each measurement point is calculated. Experiments show that measurement accuracy is close to the theoretical limits of the optical measurement system. The accuracy is sufficient for the target application.

1. Introduction

The rapidly growing number of micro-systems requires economical surface-measurement-methods to ensure geometrical accuracy of the components. The component's sizes to be measured range from a few up to a couple of hundreds of micrometers. The measurement process should easily integrate into a production system of micro-components. In order to get significant measurement results, limits and accuracy of the measurement system has to be evaluated. Target application for the measurement system described in this paper is an excimer laser system as depicted in [1], used for structuring micro-components.

The measurement system to be evaluated in this paper is a passive, optical, focus based measurement system. It consists of an optical microscope with a digital camera, a diffuse illumination unit and a micro-lift-table as positioning unit (see Fig. 1). The surface of an object on the micro-lift-table is reconstructed with a depth-from-focus approach. The focus parameter varied in this setup is the axial distance between sensor and object via the micro-lift-table. For each distance step d, a digital image I_d is taken. Local sharpness values $s_d(x,y)$ are calculated for each pixel $p_d(x,y)$ of each image I_d. Several sharpness measures have been described [2][3][4][5]. Typical measures are band-pass filtering, energy of image gradient, energy of image Laplacian and different modified versions. For an image position (x,y), the maximum sharpness value $\max_d s_d(x,y)$ of the image stack is determined. Since an object's surface appears sharpest when lying exactly in the optical systems focal plane, a depth map with discrete depth values is obtained. The depth values are then optimised by an interpolation. The interpolation is based on the sharpness characteristics of a point image of a diffraction-limited wave-optics model.

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Fig. 1 Focus based measurement system with camera and micro-lift-table

Due to the use of diffuse illumination and a focus based measurement method, only objects with structured surfaces can be reconstructed. Glass or reflective surfaces cannot be reconstructed. By verification of the sharpness values of a given image position (x, y) over the image sequence against the theoretical sharpness characteristics of a point image, invalid depth-values caused by regions without structure or high reflective areas can be detected.

In order to evaluate the system's measuring accuracy, reference-objects with precisely known geometry are needed. Therefore, a micro stair reference object, manufactured by a high precision micro cutting process, is used.

In section 2 the physical limits of the systems axial resolution are shown. Section 3 and section 4 deal with experimental results and their reproducibility. Finally, the paper closes with some conclusions.

2. Physical limit of measuring axial distances on rough surfaces

This section focuses on the physical resolution limitations along the microscope's optical axis. This axial resolution limits the minimum structure size measurable by the system. Object points with a depth difference smaller than this limit cannot be distinguished. The resolution's limitation is caused by the wave-nature of light.

According to [6], the minimal distance for distinguishing two separated points is related to the axial uncertainty of the measured distance d_z when measuring rough surfaces. The axial uncertainty can be calculated by Heisenberg's principle. The limit of measuring uncertainty depends on observation aperture, illumination aperture, and spectral character of the used illumination. Observation and illumination aperture are modelled by the so-called numerical aperture A_n, given in the microscope's data sheet ($A_n = 0.11$). According to [7][8], the minimal measurable distance is:

$$d_z = \frac{c\lambda}{2\pi A_n^2} \qquad (1)$$

The speckle contrast c depends on the light source's character. Coherent light has a speckle contrast close to $c=1$, incoherent light has a speckle contrast close to zero. According to [9], a speckle contrast less than $c=0.1$ is hardly reachable in practical applications. The system uses a diffuse white light source. In order to get a rough estimate of the axial resolution, the speckle contrast is assumed to $c=0.1$ and as representative wave length λ=633 nm is chosen. This results in an axial measurement uncertainty of $d_z \approx 0.8\mu m$. It has to be emphasized that this value is only a rough estimate, used to evaluate the measurement results.

3. Experimental accuracy evaluation

For experimental accuracy evaluation, a micro stair reference object manufactured by a high precision micro cutting process has been used. The stair is made of aluminium titanium carbonite and has five steps of different sizes. The step sizes are increasing (4.7 µm, 8.25 µm, 16.05 µm and to 29.8 µm), the lateral base of each step is 250 µm *x* 250 µm. The accuracy of the reference object has been verified by a tactile measurement system and a white light interferometer with resolution accuracy in sub-micrometer range. Figure 2 shows a depth-map and a profile view of the reference object acquired by the white light interferometer. The profile view shows two marked positions at the last two steps with a step size of 29.8 µm.

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Fig. 2 Depth map and profile view of the stair measured with a white light interferometer

In order to evaluate the measurement system's axial resolution, the reference object's surface has been reconstructed. Therefore, a sequence of 99 images of the object has been acquired. The lift-table's position was equidistantly raised by 1.3 µm between each shot. As local sharpness measure the variance in a 5x5 pixel window has been chosen. In Figure 3 a reconstructed depth-map of the reference object can be seen. Each depth value is represented by a different grey value; black areas symbolise measurements automatically recognized as invalid by the system. This outlier elimination has been performed by comparing the sharpness curve $s_d(x,y)$ of each image position (x,y) over the sequence with the sharpness characteristics of a point image of a diffraction-limited wave-optics model [10]. The image shows three of the reference object's five steps.

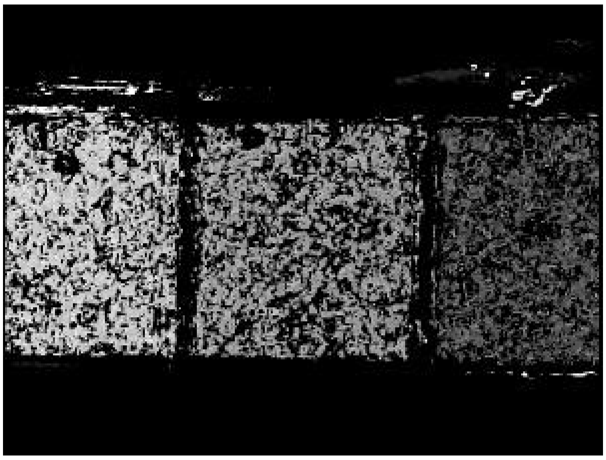

Fig. 3 Reconstructed depth-map of the stairs with step height distance 16.05 µm and 29.8 µm

To give an impression of the variance of the depth values, figure 4 shows a three-dimensional side view on the reconstructed object. The object is represented as a cloud of points.

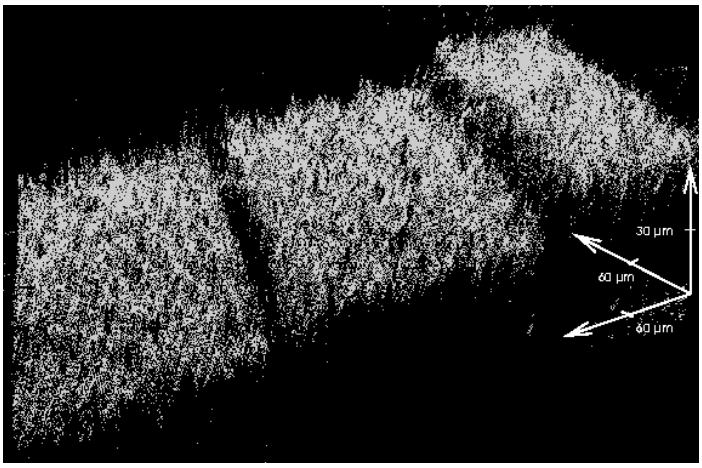

Fig. 4 Cloud of points of reconstructed stairs with step sizes of 16.05 µm and 29.8 µm

Then a mean depth difference between two adjacent steps was calculated from the cloud of points. The depth map has been segmented into rectangular areas, each area representing a single step of the reference object. Hereafter, a plane was fitted into the three dimensional cloud of points of each step by regression. The regression minimizes the mean-squared distance between all points of the cloud and the resulting three-dimensional plane. Finally, the height differences have been calculated from these planes. In figure 5 projections of the clouds of points and the calculated planes are shown.

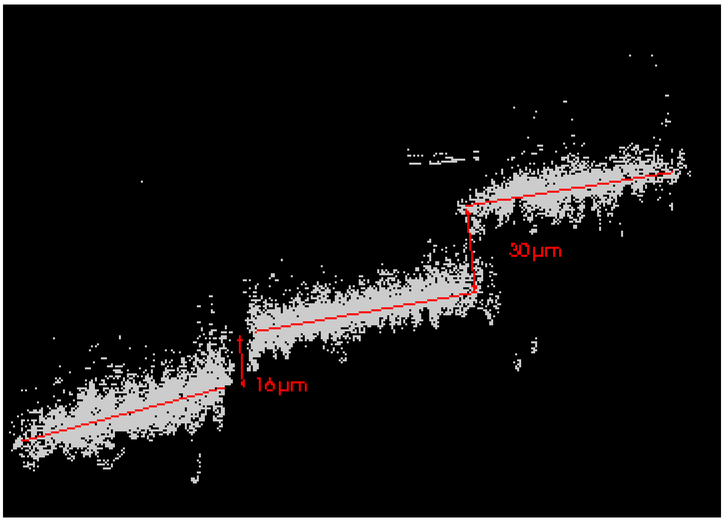

Fig. 5 Planes fitted in cloud of points

The overall reconstruction process has been repeated 50 times. Figure 7 presents the normalized density distribution of measurements for the reference object's four different step sizes without (a) and with (b) automatic outlier elimination. The abscissa shows the reconstructed depth difference between adjacent steps, the ordinate shows the normalized density of measured depth differences. The maximums of each curve are quite close to the real depth differences (4.7 µm, 8.25 µm, 16.05 µm and to 29.8 µm). The outlier elimination leads to more accurate values, i.e. higher and narrower curves around these maxima.

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Fig. 6 Result overview for the different step heights

Table 1 presents the mean value and the associated standard deviation of the reconstructed depth differences between adjacent steps of the reference object. Without outlier elimination, the deviation between reference values measured with the white light interferometer and the mean value of the described reconstruction process is less than 0.5 µm, the standard deviation is less than 1.33 µm. With outlier elimination, these values could be improved to 0.3 µm and 0.5 µm respectively.

Reference value	Without outlier elimination		With outlier elimination	
	Mean-value	Standard deviation	Mean-value	Standard deviation
[µm]	[µm]	[µm]	[µm]	[µm]
4.7	5.21	1.33	4.6	0.49
8.25	8.19	0.72	8.24	0.43
16.05	15.93	0.34	16.06	0.23
29.8	29.53	0.33	29.72	0.23

Table 1: Overview of standard deviation and mean values of the result for a measurement without and with outlier elimination.

4. Reproducibility of the results

In this section the system's measurement reproducibility is evaluated. Therefore a reference object has been reconstructed several times without changing its lateral position on the micro lift-table between the reconstruction procedures. As reference object a planar aluminium titanium carbonite ceramic has been used. Its surface was smoothed by a nano machining process so that the maximal surface slope is less than 10nm/mm. For each reconstruction procedure a sequence of 50 images was taken. Between two consecutive shots, the reference object was lifted by 2.5 µm. For each pixel position and each image a local sharpness value was calculated. From these values depth maps were calculated by finding the maximal sharpness of each image position in the image sequence. Invalid measurements again were detected by comparing the sharpness curve $s_d(x,y)$ of each image position (x,y) over the sequence with the sharpness characteristics of a point image of a diffraction limited wave optics model. In order to improve the axial resolution, this model has also been used to estimate the depth of maximum sharpness with sub slice precision, i.e. d is no more limited to the lift-table's step size.

The overall reconstruction procedure has been repeated twelve times. After outlier elimination for each image position the variance of the measured depth values has been calculated. It turned out, that these variance values are normally distributed over the image. The average variance is shown in table 2 without (a) and with (b) interpolation of the depth values. Different window sizes for calculation of the sharpness values have been examined.

The table shows a significant improvement of about factor 3 by using the optical model for interpolation of depth values. Choosing a larger window size for calculating the local sharpness measure also leads to better reconstruction results. Unfortunately, it comes a long with degradation of the system's lateral resolution.

Window Size [pel x pel]	Standard deviation without interpolation	Standard deviation with interpolation
3x3	7.5	2.8
5x5	5.1	1.4
7x7	4.1	0.9
9x9	3.5	0.6
11x11	3.1	0.5

Table 2: Influence of the window size on the measurement results

5. Conclusion

The accuracy of a passive, optical, focus based measurement system has been evaluated. It is influenced by many parameters that can be separated into three classes. Firstly, there are parameters given by the used hardware. The system's optical quality as well as the character of the used illumination limits the system's theoretical depth resolution. In general incoherent light sources lead to a better resolution than coherent ones. The mechanical precision of the micrometer lift-table for sure also affects the system's accuracy. Secondly, the measurement object's surface structure, especially its roughness, is relevant. Glass or other reflective surfaces like mirrors do not show considerable information. Therefore they can hardly be reconstructed by an image based reconstruction approach. Eventually, the reconstruction algorithm and its parameters affect the measurement accuracy. As sharpness measure for the focus based measurement system, the local variance was chosen. The influence of the window size has been examined.

The experimental results lie close to the roughly estimated theoretical limits of the optical measurement system. The deviation of the measured mean values from the reference values and the associated standard deviations are less far than 1 µm. The system's accuracy was significantly improved by an outlier elimination. The optical model used for outlier detection has also been used to improve the system's axial resolution. A larger window size improves the reproducibility of measurements, but reduces the system's lateral resolution. Altogether, the system's axial accuracy is close to theoretical limits. A further task not stated in this paper is to expand the system in order to improve the lateral resolution.

The system's accuracy meets the requirements of the target application. For the use of the sensor in a laser system of the “Laser Zentrum Hannover e.V.” a lateral measurement range of 1 mm^2 and an axial measurement range of 200 mm is possible as a result of the chosen lift-table. With a bi-directional repeat accuracy of 2 µm according [11] we got a relative axial accuracy of the sensor of 1/100000.

6. References

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