MODELING, DESIGN AND CONSTRUCTION OF A SIMPLE LASER SCANNING MICROSCOPE

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Abstract. *Laser Scanning is a wide spread technology largely used in many different areas and plays an important role in the fields of nanotechnology and metrology. It expands the optical limits of conventional microscopes and offers fast, accurate and repeatable measurements. This article presents the design and construction of a simple Laser Scanning Microscope for surface metrology in millimeter range with nanometer resolution. The system is based on the lateral scanning of samples through the deflection of a laser beam with the use of a 2D rotating mirror and on a depth scanning through the displacement of the objective and an astigmatic focus detection procedure. Initially a brief introduction of the system's working principle is presented, followed by a detailed description of the designed scanning microscope and its simulation using a specially developed software. The constructed system is then presented and the first practical results and measurements are presented and discussed. The construction of the presented laser scanning microscope aims at the development of a simple and versatile microscope for surface metrology and to offer an experimental set-up for the measurement and analysis of different system parameters and their influence in overall system performance.*

Keywords: *Laser Scanning Microscopy, Metrology, Optics, Autofocus*

1. INTRODUCTION

Laser Scanning is a wide spread technology largely used in many different areas, from data storage and barcode readers to manufacturing and microscopy. Its first concepts were developed in 1957 by Marvin Minsky (Minsky, 1961) and it is today an established and widely used technology. It is basically a technique for increasing contrast and resolution in optical imaging systems through the rejection of out-of-focus light. Images are acquired point-by-point and reconstructed with a computer, allowing optical sectioning, expanding the optical limits of conventional microscopes and offering fast, accurate and repeatable measurements.

This article presents the design and construction of a simple Laser Scanning Microscope for surface metrology in millimeter range with nanometer accuracy. The system is based on the lateral scanning of samples through the deflection of a laser beam with the use of a 2D rotating mirror and on a depth scanning through the displacement of the objective and an autofocus procedure.

Initially a brief introduction of the system's working principle is presented, followed by a detailed description of the designed scanning system and its simulation using a specially developed software (Ginani and Theska, 2009). Afterwards the proposed system is theoretically analyzed and its main functional parameters determined and discussed. The constructed system is then presented and the first practical results and measurements are presented, compared with the theoretical model and discussed.

The construction of the presented laser microscope aims at the development of a simple and versatile microscope for surface metrology. In this initial phase, in order to validate the system's functionality, it was tested using an epiplan-neofluar objective, but the next step is to replace this complex optical system, for a single simple optical lens, reducing costs and the weight of the movable focusing optics, therefore improving measurement speed and system dynamics.

The use of simple uncorrected optics inserts optical aberrations in a system and deteriorates its performance. The traditional way of solving this problem is to improve the optical system such that it works as a perfect lens, but often that comes with the price of heavy and costly optics. Having in mind the computer power available nowadays, it is now possible to consider unconventional alternatives to optics optimization. By breaking the paradigm of improving the optics to a perfect lens, it is possible to use simple optics and correct its optical errors computationally.

2. SYSTEM DESIGN AND SIMULATION

The constructed laser scanning microscope is based on the lateral scanning of samples through the deflection of a laser beam with a 2D tilting mirror, and on a depth scanning through the displacement of the objective with the help of an autofocus sensor.

Figure 1 illustrates the system configuration and its components. The system uses a hologram laser unit (Mastylo *et al.*, 2005) that generates a 650nm beam. The laser beam is collimated and then deflected with a 2D tilting mirror. The deflected laser is then focused on the sample through the objective. The laser reflects on the sample and returns through the objective to the mirror where it is once again reflected back into the hologram laser unit into a photodiode detector.

The lateral position of the scanning point is determined by the mirror angles and its depth by the displacement of the objective and the use of an autofocus procedure.

Autofocus is a feature that allows optical systems to always work in focus, as illustrated in Figure 1. There are many ways to implement autofocus in optical systems. Bitte (2002) and Marshall (1991) describe some of these techniques in detail. In the developed system, autofocus is accomplished through the translation of the objective lens along the optical axis and the measurement of the focus error information contained in the laser beam using an astigmatic focus detection method (Marshall, 1991). By keeping track of this translation, it is possible to determine the depth of the focus point and therefore the depth of the sample point where the light beam is focused.

The used focus sensor is based on a hologram laser unit and works as a zero-sensor (Mastylo *et al.*, 2005). It enables the determination of the system's focal point through an analysis of the reflected light and of the formed focal point image (Fig. 1). The sensor generates, depending on the distance between sample and focus, two signals. A sum signal and a difference signal. The sum signal measures the incident energy on the sensor and the difference signal measures the symmetry of the imaged laser spot. When this signal is zero, then the laser beam is focused precisely on the sample.

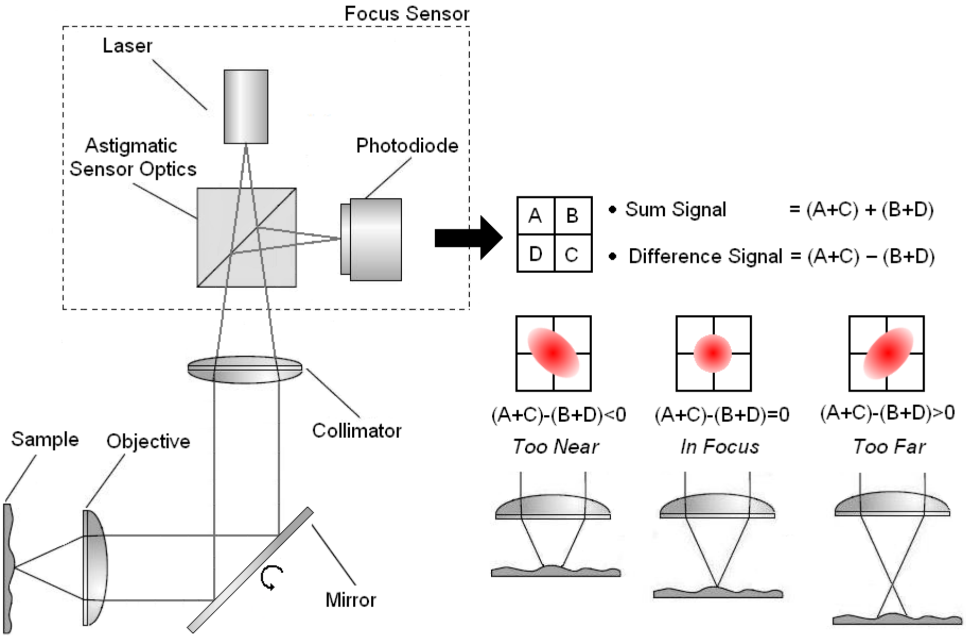


Figure 1. System Configuration and Autofocus Sensor

Figure 2 shows a simplified schematic of the scanning system and its modeling as a paraxial system.

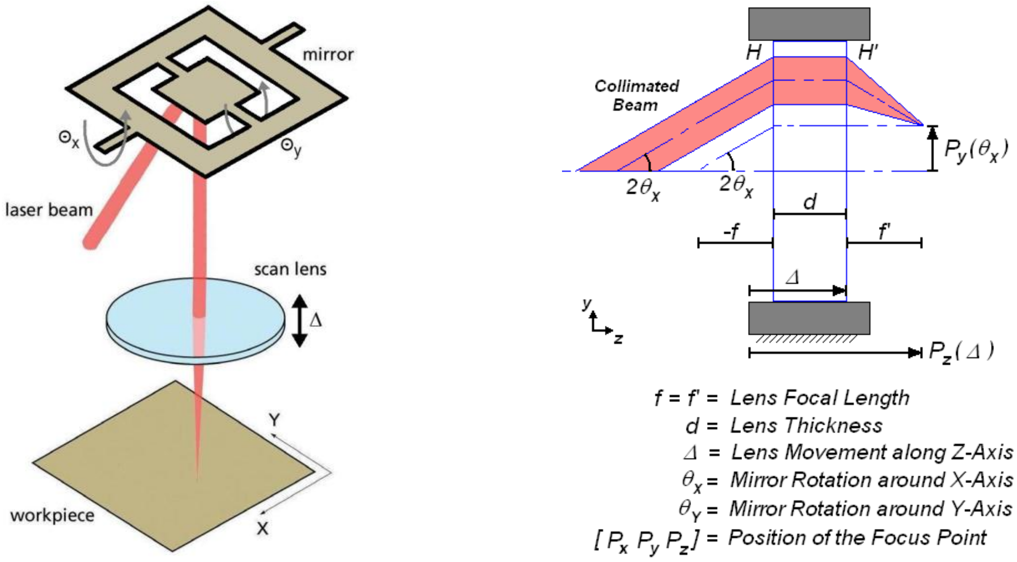


Figure 2. Scanning Schematic and Paraxial Model

Deriving the equations (Eq. 1) for the above illustrated configuration, the linear behavior of the achieved depth scanning can be observed. This linearity is one of the reasons why this optical scanning configuration is one of the most widely used in laser engraving and confocal laser microscopy (Ginani and Theska, 2010, Marshall, 1991).

$$\begin{cases} P_y(\theta_x) = f'\tan(2\theta_x) \\ P_z(\Delta) = f' + \Delta \end{cases} \tag{1}$$

Though the paraxial model offers a simple and fast way to evaluate an optical system, it applies strictly to light rays that are infinitesimally displaced from the optical axis of a system and does not take optical aberrations in consideration. When working with high precision measuring systems those aberrations play an important role and their influence should be considered. As scanning systems work with relative large incident angles, optical aberrations, if not properly addressed, are especially high by them (Gandhi and Deshmuhk, 2010, Xi *et al.*, 2007). Figure 3 illustrates the influence of these optical aberrations in the optical layout shown in Fig. 2. Using a simple plane-convex spherical lens with a focal length of 8mm, the curvature of the obtained focal surface was simulated for three different lens positions (Δ) using a ray-tracing program (Ginani and Theska, 2009).

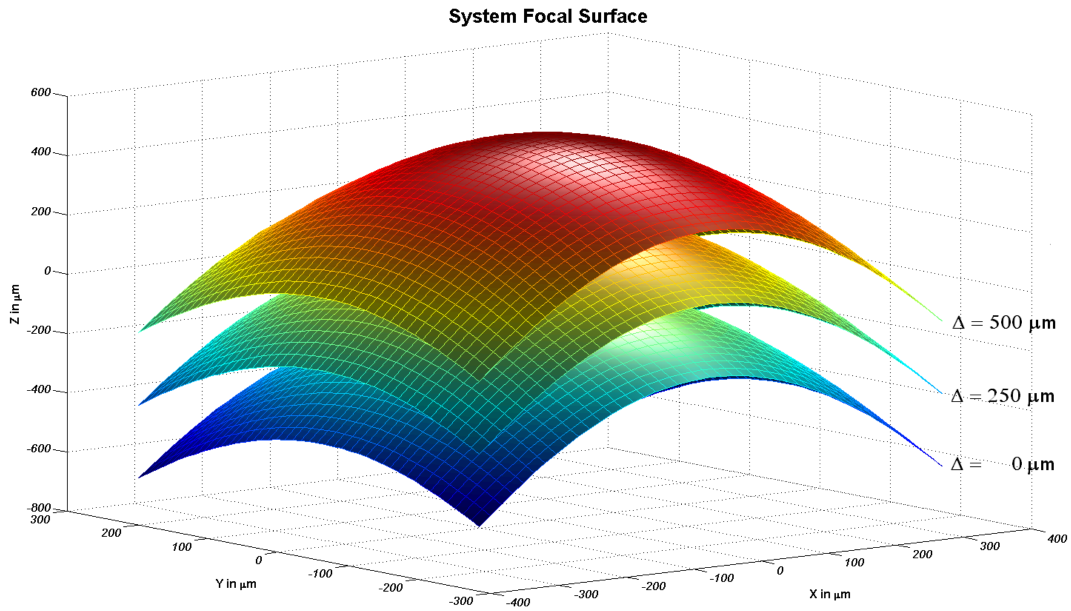


Figure 3. Simulated Focal Surface Curvature for a Spherical PCX Lens

The observed curvature generates an error of approximately 500µm on the borders of the measuring area, what is unacceptable. The traditional way of solving this problem, as mentioned earlier, is the development of complex objectives that optically compensate those errors and the use of relay optics (Beiser, 1995, Marshall, 1991). Unfortunately this often leads to costly and heavy optics, what reduces system dynamics and makes the measuring time larger.

A possible alternative solution is to correct these errors computationally. Laser scanning microscopy is a technique that acquires data from the surface point to point. With ray-tracing simulation and/or calibration of the focal curvature, the errors generated by the optical aberrations in each measuring point can be predicted or a priori measured, so that the measured data can then be corrected. Thus, with the computationally corrected data, results comparable to those obtained with optical compensation could be achieved.

3. CONSTRUCTED SYSTEM AND EXPERIMENTAL MEASUREMENTS

The constructed system is shown in Fig. 4 together with a schematic representation of its main components: The laser and the focus sensor, the tilting mirror, the microscope objective and the objective positioning stage.

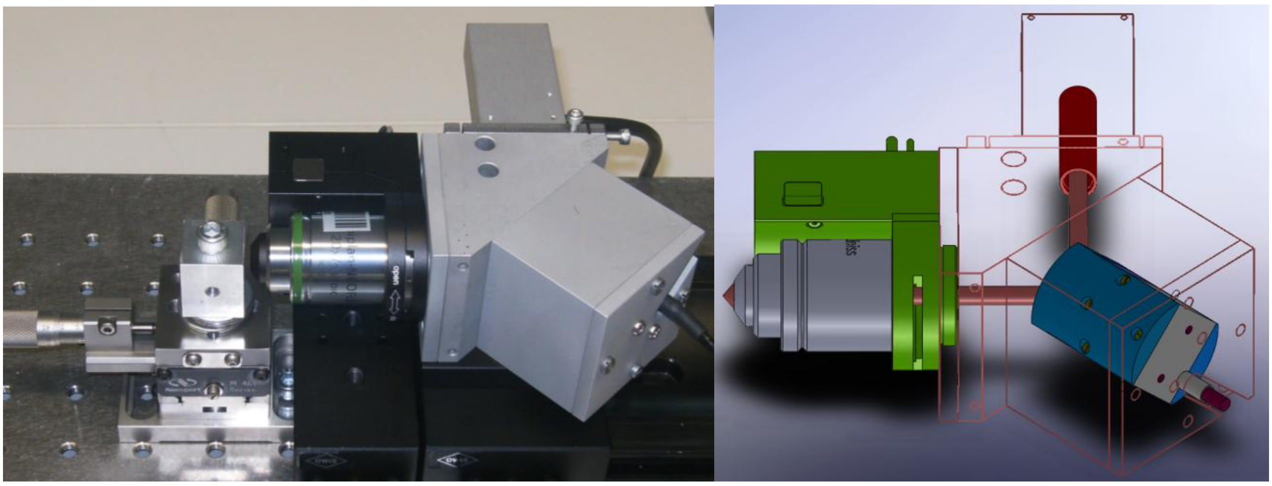


Figure 4. Developed Laser Scanning Microscope

The scanning system was designed for surface metrology in millimeter range with nanometer resolution. It uses an epiplan-neofluar objective with a focus length of 8mm and a tilting mirror platform based on piezo actuators. The axial shift of the objective is also done with the help of piezo actuators.

The tilting mirror allows a movement of ±25mrad around two fixed perpendicular axes with a resolution of 5µrad, what together with the 8mm objective offers accordingly to Eq. (1) a lateral scanning area of approximately 0.8mm x 0.8mm and a raster resolution of approximately 40nm. The translation stage allows a linear movement of 100µm of the objective with a resolution of 0.7nm.

The used epiplan-neofluar objective is a high quality microscope objective. Though the final system will use simple optics in the initial tests a good corrected optics was used. Such optical systems are designed to work as paraxial systems and therefore a highly flat focal surface should be normally expected. The designed system uses, however, no relay optics. Without the relay optics, the rotating mirror does not lie in one of the system pupils, as in usual laser scanning systems. That results in an underillumination of the objective's entrance pupil, and as microscope objectives are not designed for such circumstances, measuring errors caused by optical aberrations were expected.

After the construction of the laser scanning microscope, the first experimental measurements were carried out. In this initial phase only simple geometries were measured in order to observe the system capabilities and evaluate its performance. These measurements are a first qualitative proof of the system's functionality and also can be used to show the influence the suboptimal optical design in the final system.

As the first measuring sample a plane mirror was chosen. Plane mirrors offer a high smooth and flat surface with surface accuracy in nanometer range and are therefore ideal samples. They offer an a priori known geometry, so that all measured deviations can be ascribed to the measuring system. Figure 5 shows the measured mirror surface.

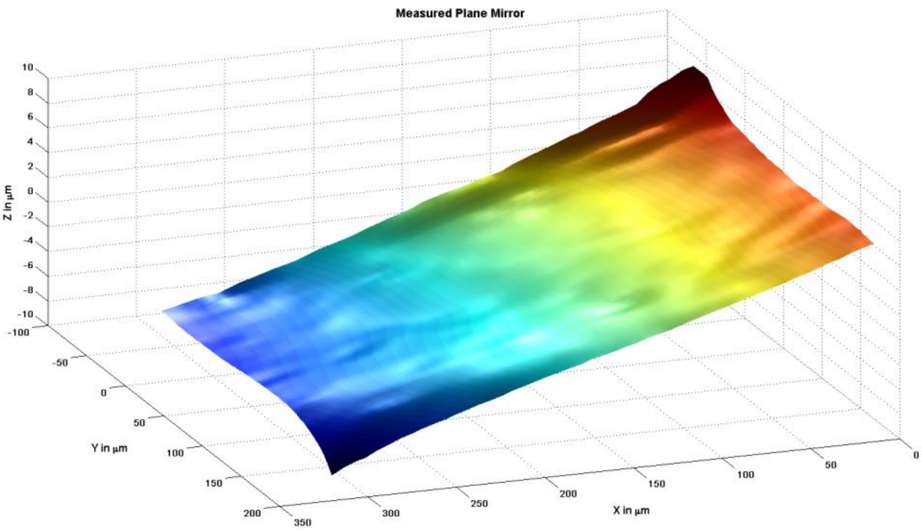


Figure 5. Measured Plane Mirror

The measured surface can then be used to observe and evaluate the system's field curvature. When the measured mirror surface is regarded as a perfect plane, then all observed deviations are, as explained, due to the measuring system. Based on this premise, Figure 6 shows the focus surface of the system with the epiplan-neofluar objective.

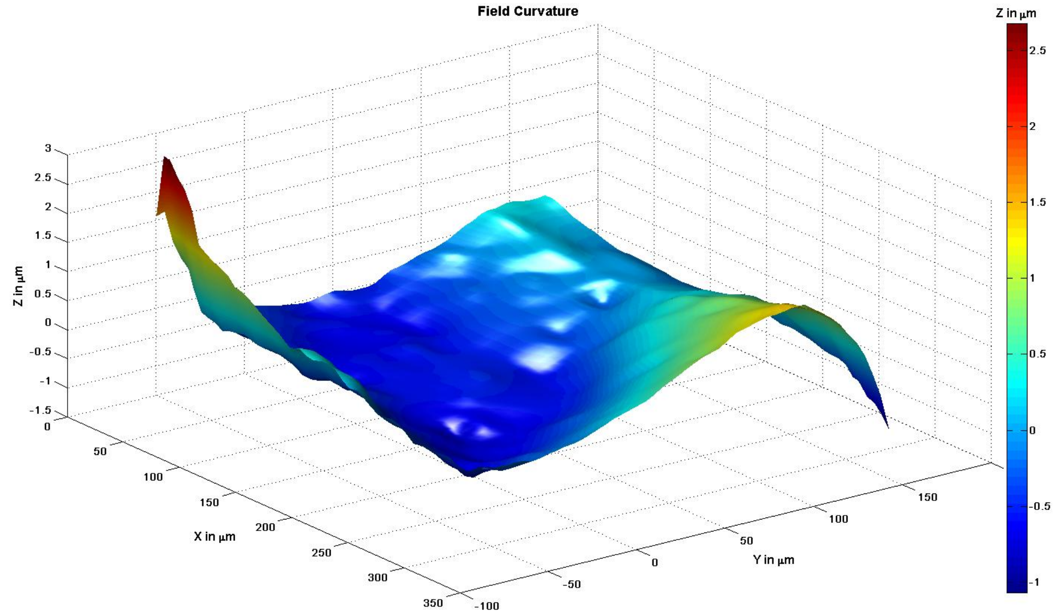


Figure 6. Observed System Focal Surface

As expected the microscope objective presents a curvature caused by the underillumination of the entrance pupil. The observed focal surface is symmetrical and has a maximum deviation of 3.5µm in the measured area. For implementing an error correction strategy it is vital to know the focal surface curvature. Therefore further investigations on the obtained surface are still needed, especially regarding repeatability of the measured values.

Figure 7 and 8 show the measurement of two other different samples. Firstly in Fig. 7 a steal sphere with a diameter of 1mm was measured. Although steal spheres have a significant surface roughness, they also offer a known geometry and, even more, they offer a continuous variation of the surface normal. As the surface changes, so does the direction of the reflected laser rays. If this inclination is too steep, then the reflected laser can not be imaged by the optical system anymore and therefore can not be measured. With a continuous variation of the surface slope, it is possible to observe how this inclination influences the measurement.

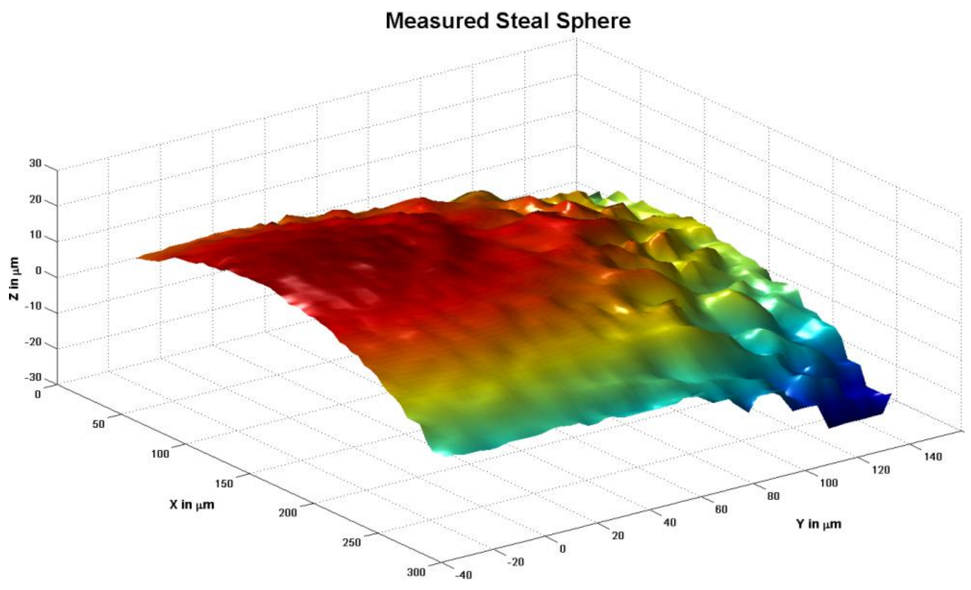


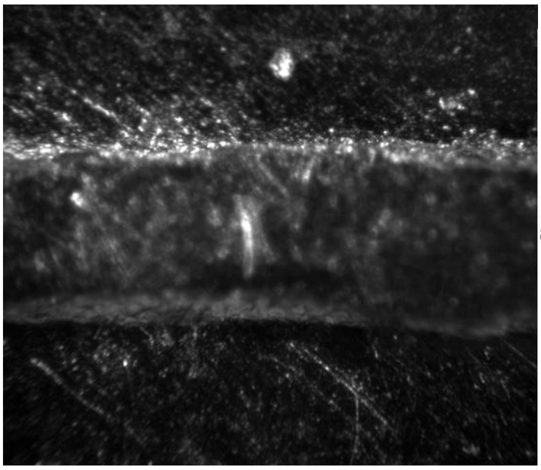
Figure 7. Measuring of a Steal Sphere with 1mm Diameter

Analyzing the obtained data and the reconstructed surface, a higher noise was observed on the edges of the measuring area. This behavior was already expected. Optical systems have a limited aperture and, when the sample surface has a high slope, not all the reflected light can be captured by the lenses. With less light in the system, the noise tendency is to grow, as observed in Fig. 7.

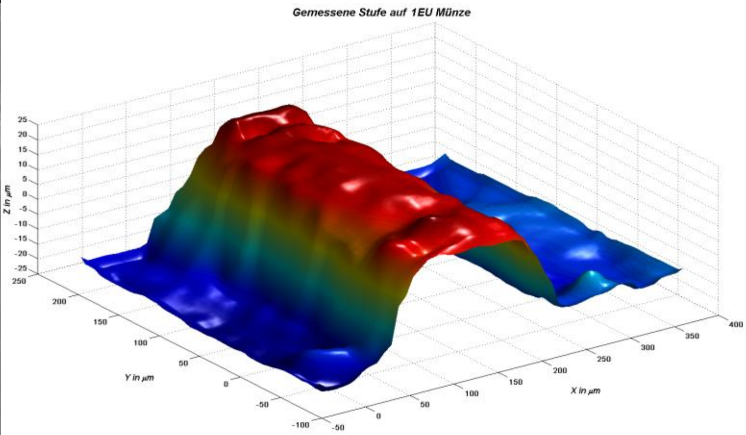
Considering only the measured lateral region where the observed noise was qualitatively small, it is possible to determine a rough estimative of the maximal reliable measurable inclination. For the actual system configuration the obtained value was ±15°.

The second sample used, shown in Fig. 8, was a step on a copper-nickel coin. In Fig. 8a a picture of the step geometry is shown. The picture was taken using a magnification of 6X and a CMOS-Camera. In Fig. 8b the measured step surface is illustrated.

The sample offers a qualitatively known geometry, but roughness, surface defects and eventual shape deviations are unknown, so that the coin offers a valid sample for qualitative purposes only. It illustrates the measuring of a sharp edge, but a quantitative evaluation of the measured surface would not be metrologically valid.



(a)



(b)

Figure 8. (a) Microscope Picture of a Stamped Line on a Coin (b) Line Measured with the Laser Scanning Microscope

Though a quantitative evaluation of this measurement does not offer comparison data, still a few values can be extracted from the obtained surface. The measured step has a height of 35µm and a width of 150µm. The system also showed a good behavior in the measured sharp edges. No batwing-effect (Leach, 2010) was observed and the obtained step geometry was correctly measured.

4. CONCLUSION

In this paper the design and construction of a simple and versatile microscope for surface metrology was presented and described. The system was firstly modeled in the paraxial region and then simulated using spherical lenses and a specially developed ray-tracing simulator.

The basic working principle of the system was presented and its functionality was demonstrated through a series of experimental measurements in different samples.

Future work includes a deeper analysis of the developed laser scanning microscope, the analysis of the optical aberrations and error sources in the system and the development of correction strategies for these errors in order to improve system performance.

5. ACKNOWLEDGEMENTS

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