A novel approach to laser scanning microscopy using error correction algorithms

Luciano Selva Ginani[1,#] and **René Theska**[1]

1 Department of Precision Engineering, Ilmenau University of Technology, Newtonbau, Gustav-Kirchhoff-Platz 2, 98693, Ilmenau, Germany
Corresponding Author / E-mail: luciano.ginani@tu-ilmenau.de, TEL: +49 (0) 3677-69-3826, FAX: +49 (0) 3677-69-3823

KEYWORDS : Laser Scanning Microscopy, Optics, Optical Aberrations, Nanometrology

This article presents the design and construction of a laser scanning microscope based on autofocus for surface metrology in millimeter range with nanometer resolution. The proposed system is theoretically analyzed and the first practical results and measurements are presented and discussed. Initially, 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 uncompensated 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. By breaking the paradigm of improving the optics to a perfect lens, a new approach to scanning microscopy is proposed, by using simple optics and correcting its optical errors computationally.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

1. Introduction

In 1957 Marvin Minsky presented for the first time his invention of a microscope system capable of rejecting all scattered light, except that emanating from a single focused point [10]. His objective was to permit a high selectivity of light in order to reduce blurring and achieve a higher resolving power than conventional microscopy. More than 50 years after, Minsky's apparatus is today the base of scanning microscopy and a wide spread technology largely used in many different areas. Biology, metrology, medicine, microelectronics are a just few examples of the variety of fields in which scanning microscopy is successfully used.

This article presents the design and construction of a Scanning Microscope for surface metrology in millimeter range with nanometer resolution. The system's working principle is presented together with the modeling and simulation of the proposed scanning system. The constructed system is then presented and a series of initial measurements are presented and discussed.

The construction of the presented laser microscope aims at the development of a simple and versatile microscope for surface metrology and for the experimental measurement of optical errors that emerge from the use of suboptimal optics in scanning microscopy.

The use of simple uncompensated 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. With a previous knowledge of the occurring errors, it is possible to correct those errors computationally. That would allow the use of simpler optics in scanning systems, reducing overall weight, raising system dynamics and reducing costs, without losing accuracy.

Initially, in order to validate the system's functionality, it was tested using a high quality microscope objective, but aiming at the replacement of this complex optical system, an initial evaluation of an aspheric singlet is presented, comparing experimental and simulation results and discussing the use of different strategies for the computational correction of the measuring data.

2. System Design and Simulation

2.1 System's Basic Structure

The proposed design is based on three main points. A lateral pre-scanning using a tilting mirror, a depth scanning through the displacement of the focusing objective along the optical axis and the detection of the focus position with the use of an astigmatic focus sensor.

Figure 1 shows a schematic drawing of the system's configuration and its main components. The system uses a hologram laser unit [9] from conventional DVD technology that generates a beam with a wavelength of 654nm. The generated 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 laser unit includes the diode laser, a beam splitter and a diffracting grating for generating the astigmatism necessary for measuring the focus length and implementing the autofocus feature in the system. With the autofocus, the system is able to always work in focus, as illustrated in Figure 1. There are different ways to implement autofocus [3, 8]. In the developed system, it is accomplished through the movement of the objective along the optical axis and the measurement of the focus error information contained in the laser beam using an astigmatic focus detection method [8].

The focus sensor is used as a zero-sensor [9]. 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.

By measuring how far the objective must be moved until the difference signal is zero, it is possible to determine the depth of the point where the laser beam is focused on the sample.

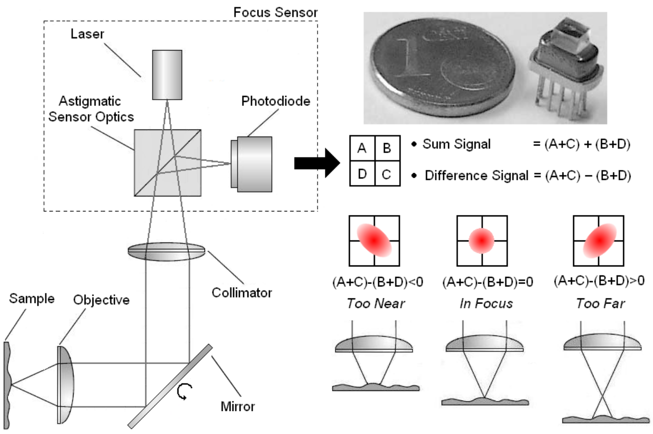


Fig. 1 System Basic Schematics and Astigmatic Autofocus Sensor

2.2 System's Paraxial Modeling and Ray-Tracing Simulation

Paraxial optics, also known as Gaussian optics, is the simplest way of describing an optical system [7]. It is a method of determining the first-order properties of a system, assuming that all ray angles are small and in the vicinity of the optical axis. It offers an easy and fast framework in which optical characteristics of a system can be observed and analyzed.

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

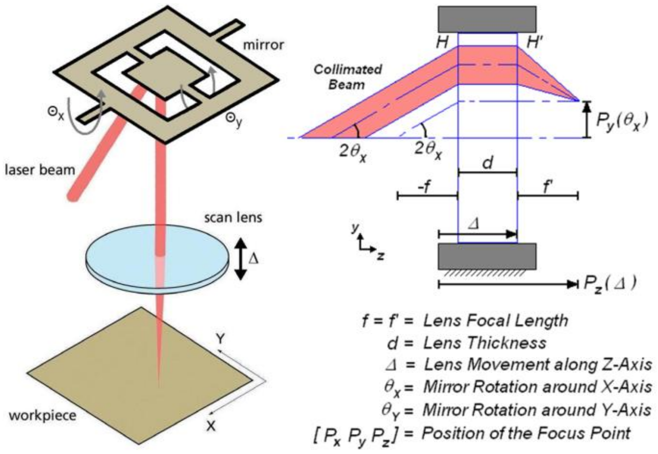


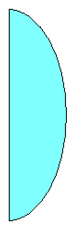
Fig. 2 Scanning Schematic and Paraxial Model

Deriving the equations (Eq. 1) for this configuration, the linear behavior of the obtained depth scanning can be observed. This linearity is one of the main reasons why this optical scanning configuration is largely used in laser engraving and confocal laser microscopy [5, 8, 11].

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

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 and does not take optical aberrations in consideration. When working with precision systems, optical aberrations play an important role and as scanning systems work with relative large incident angles, optical aberrations, if not properly addressed, are especially high [4, 12]. Figure 3 illustrates the influence of these optical aberrations in the optical layout shown in Fig. 2. Using a simple plane-convex aspheric lens described by Eq. 2 [7] and the coefficients in Tab. 1, the curvature of the obtained focal surface was simulated for three different lens positions (Δ) using a specially developed ray-tracing software tool [6].

$$Z(r) = \frac{C.r^2}{1+\sqrt{1-(K+1)C^2r^2}} + K_2r^2 + K_4r^4 + \ldots \tag{2}$$



n = 1.58618

Lens Parameters	
Width	*5.5mm*
C	*0.113122*
K	*-1.427973*
K_2	*0*
K_4	*1.577441E-04*
K_6	*-6.152039E-08*
K_8	*8.528969E-10*
K_{10}	*-3.504659E-12*
K_{12}	*0*

Table. 1 PCX Aspheric Lens Parameters

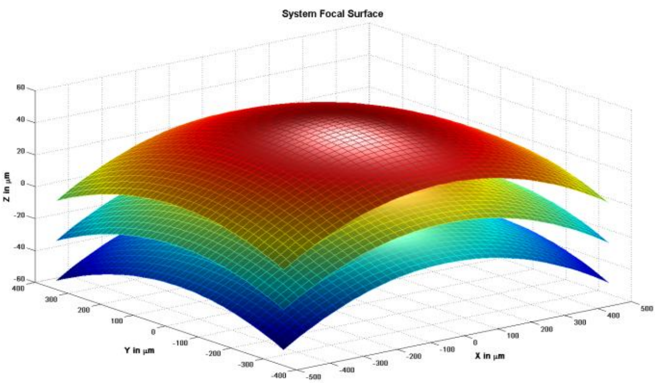


Fig. 3 Simulated Focal Surface Curvature for an Aspheric PCX Lens

The simulated surface, shown in Fig. 3 illustrates the importance of ray tracing simulation for analyzing an optical system out of the paraxial region. The influence of optical aberrations, especially field curvature, is clearly shown in the simulated focal surface. The observed curvature generates an error of approximately 50µm on the borders of the measuring area. This error can be as big as 500µm and even larger depending on the used lens, the incidence angles and other configuration parameters [5].

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 lenses for positioning the tilting mirror in an optical pupil [1, 8]. Unfortunately this often leads to costly and heavy optics.

A possible alternative solution is to correct these errors computationally. Scanning microscopy is a technique that acquires data from the surface point to point. With ray-tracing simulation, the errors generated by the optical aberrations in each measuring point can be predicted, so that the measured data can then be corrected. This way, the computationally corrected system would be able to achieve results comparable to those of optical compensated systems.

3. Constructed System and Experimental Measurements

The constructed system (Fig. 4) 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.

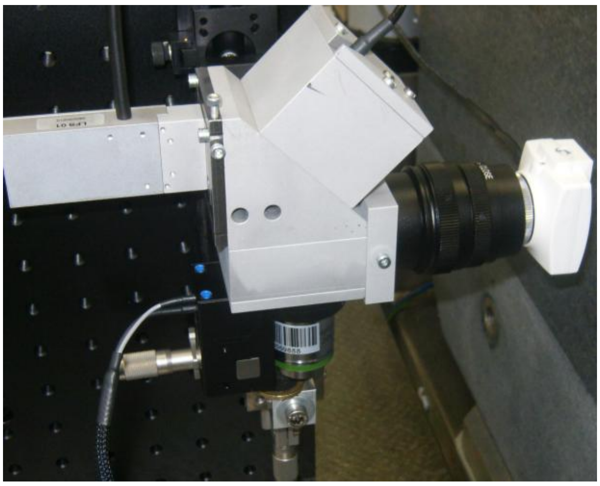


Fig. 4 Developed Laser Scanning Microscope

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 step width of approximately 40nm. The translation stage allows a linear movement of 100µm of the objective with a resolution of 0.7nm.

The system also features a camera for assisting in the positioning of the probe in the working area of the microscope and for observing the scanning procedure.

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 compensated 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 lenses. 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. Microscope objectives are not designed for working as scanning lenses and therefore, the occurrence of optical aberrations was 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 the influence of the suboptimal optical design in its performance.

As the first measuring sample a plane mirror was chosen. Precision plane mirrors are often used in high-end optics applications and offer a smooth and flat surface with surface accuracy in nanometer range and a high reflectivity. As the developed system works with reflected light, a plane mirror is an ideal sample. They also 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.

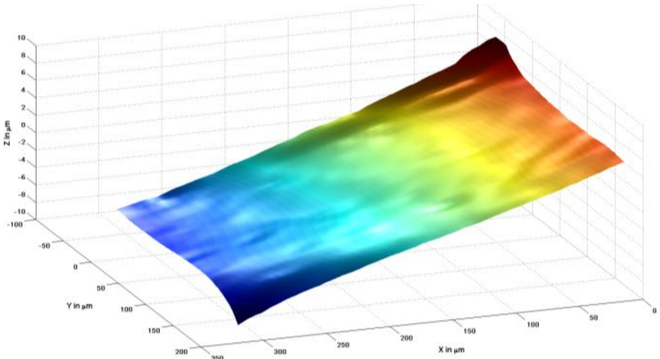


Fig. 5 Measured Plane Mirror

The measured data (Fig. 5) shows a smooth surface with a slight tilt of approximately 3° in relation to the optical/measuring axis. A small curvature can also be observed, especially on the corners of the measuring area.

The mirror surface, as explained earlier, can be considered a perfect plane. By doing so, all observed deviations are due to the optical system. Fitting a plane to the measured data using a least square fit and plotting only the observed deviation, then the obtained curvature will be the optical system's field curvature. Using this procedure, Fig. 6 shows the measured focus surface using the epiplan-neofluar objective.

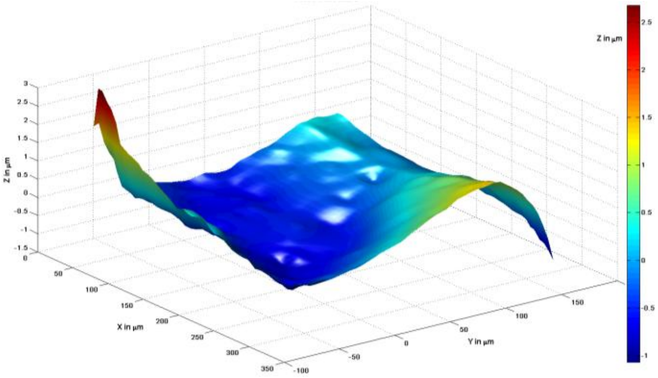


Fig. 6 System Focal Surface with an Epiplan-Neofluar Objective

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. Steal spheres 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.

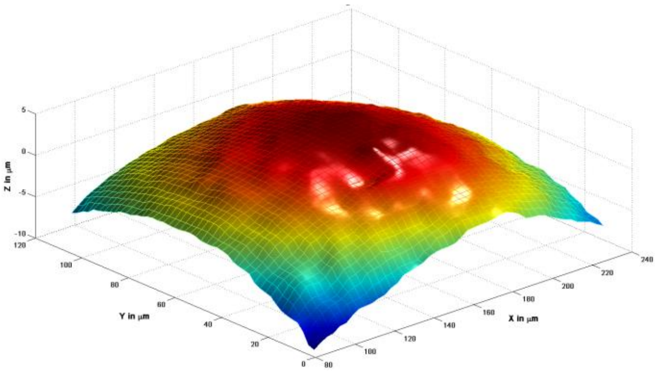


Fig. 7 Measuring of a Steal Sphere with 1mm Diameter

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.

The second sample used was a grating structure on a nickel-brass coin. In Fig. 8a a microscope picture of the grating geometry is shown. The picture was taken using the integrated CMOS-Camera (Fig. 4) and a 50mm lens, what in combination with the 8mm focal length of the microscope objective results in an image ratio of 6.25 [2, 7]. In Fig. 8b the measured step surface is illustrated.

The coin structure offers a qualitatively known geometry, but roughness, surface defects and eventual shape deviations are unknown. Therefore, it offers only a qualitative evaluation of the system and its behavior with relative sharp edges.

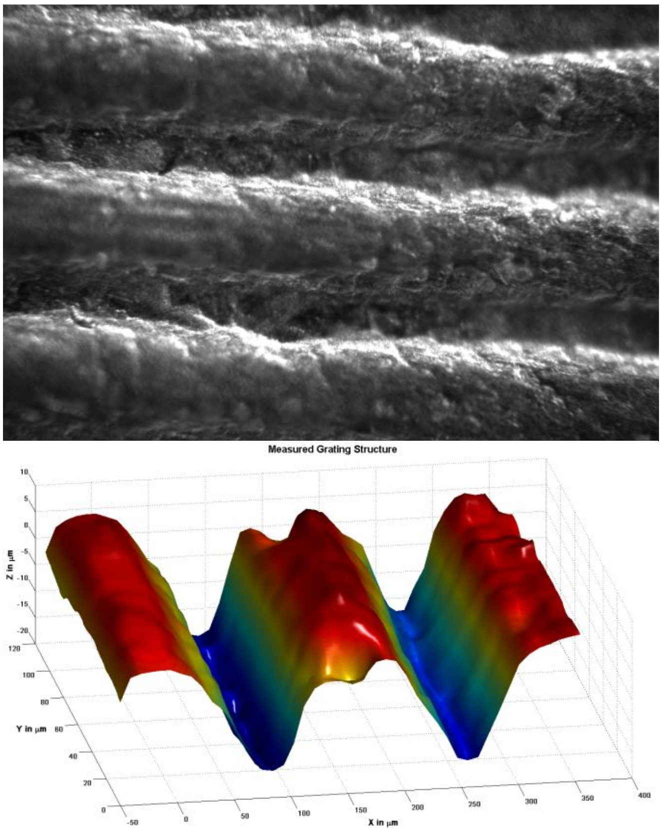


Fig. 8 (a) Microscope Picture of a Grating Structure on a Coin
(b) Measured Grating with the Laser Scanning Microscope

Though a quantitative evaluation of this measurement is, as explained, not possible, still a few values can be extracted from the obtained surface. The measured grating has an average height of 25µm, a width of 75µm in the higher plateau and of 30µm in the lower plateau.

4. Computer Aided Error Correction

As illustrated earlier, the use of uncompensated optics or suboptimal optical design accentuate the influence of optical aberrations in the system and introduce errors in the measurement results. The field curvature observed in Fig. 3 and in Fig. 6 are examples of this influence.

Replacing the epiplan-neofluar objective by the aspheric singlet described in Tab. 1 and remeasuring the mirror surface using the same procedure used to obtain Fig. 6, the field curvature for the asphere can also be experimentally measured. Figure 9 shows the obtained field curvature.

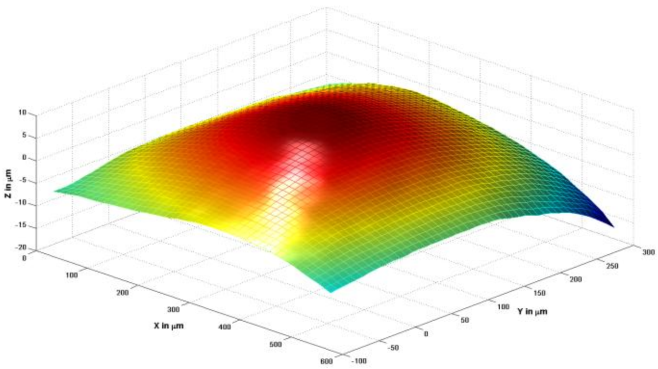


Fig. 9 System Focal Surface with an Aspheric Singlet

The measured curvature is larger than that observed when using the epiplan-neofluar objective. While the deviations of the compensated microscope objective lie around 3.5µm, the uncompensated asphere has deviations up to 50µm.

Nevertheless, the experimental data is similar to the simulated data in Fig. 3. Comparing both obtained surfaces, the difference between the simulated and measured curvatures can be calculated and used to validate the ray-tracing model of the system.

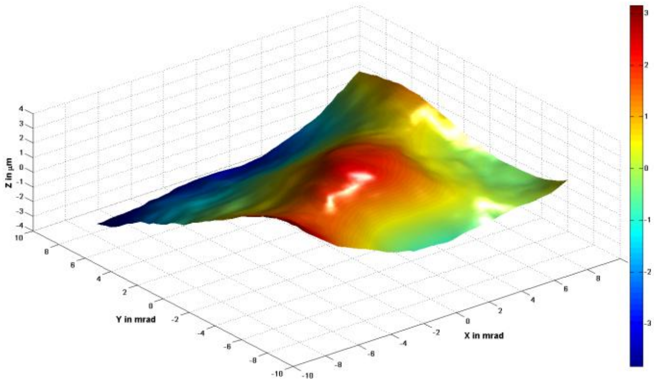


Fig. 10 Difference between Measured and Simulated Focal Surface

The observed error between the modeled and the real system, as shown in Fig. 10, is in the order of 6.5µm (Peek-to-Valley). Therefore a correction of the measured data using the developed ray-tracing model would yield a measuring error in the same order. This shows that the use of a computational model to correct the measured data has the potential to improve the system to a higher level of accuracy, similar to that obtained with an optical compensated system.

At the moment, the model does not take in consideration possible deviation of the real microscope in relation to its theoretical design, so that, with further improvements in the system's model, the errors observed in Fig. 10 can still be strongly reduced.

The same correction strategy could also be used for improving the measurements made with the epiplan-neofluar objective, but only experimentally, as information about the optical design of such objectives is normally not available.

5. Conclusions

In this paper the design and construction of a simple and versatile microscope for surface metrology was presented and described. Its basic working principle was presented and the system was modeled in the paraxial region and simulated with a ray-tracing tool using an aspheric singlet.

The constructed microscope was presented and its functionality was demonstrated through a series of experimental measurements in different samples.

The use of uncompensated optics in scanning microscopes was discussed and the advantages and disadvantages regarding system dynamics, costs and optical aberrations were highlighted. The influence of optical aberrations in the measurement results when using uncompensated optics was also discussed and a possible correction strategy based on the use of ray-tracing simulation was proposed.

The first obtained results were positive and promising. They demonstrate that the use of error correction algorithms is a viable alternative to the traditional cost and volume driving optimization of the optical system.

Future work includes a deeper analysis of the developed laser scanning microscope and the implementation of correction strategies for these errors in order to improve system performance and compare the results with those obtained with the use of compensated optics.

Further investigations regarding repeatability of the observed optical aberrations are also needed, especially regarding the independence between the errors introduced by the uncompensated optics and the sample geometry.

ACKNOWLEDGEMENT

This work was supported by the Johannes Hübner Stiftung (*www.johannes-huebner-stiftung.de*).

REFERENCES

1. Beiser, L., 1995, "Fundamental Architecture of Optical Scanning Systems", Applied Optics, Vol. 34, Issue 31, pp. 7307-7317.
2. Beyer R., 1988, "Handbuch der Mikroskopie", VEB Verlag, Berlin, Germany, 488p.
3. Bitte, F., 2002, "Ein Spiegelmatrix-Basiertes Optisches 3D-Messsystem für die Mikrostrukturprüfung", Ph.D. Dissertation, RWTH-Aachen, Aachen, Germany.
4. Gandhi, P.S., Deshmukh, S., 2010, "A 2D Optomechanical Focused Laser Spot Scanner: Analysis and Experimental Results for Microstereolithografy", J. Micromech. Microeng., Vol. 20, Issue 1, pp. 001-011.
5. Ginani, L.S., Theska, R., 2010, "Investigation of Opto-Mechanical Scanning Systems with the use of a Ray-Tracing Tool", 2010, EUSPEN, Delft, Holland.
6. Ginani, L.S., Theska, R., 2009, "Development of a Software Simulation Tool for Movable Optic Components", Proceedings of the 20th Brazilian Congress of Mechanical Engineering, Gramado, Brazil.
7. Haferkorn, H., 1994, "Optik: Physikalisch-technische Grundlagen und Anwendungen", Ed. Barth, Leipzig, Germany, 691p.
8. Marshall, G.F., 1991, "Optical Scanning", Marcel Dekker Inc., New York, USA, 896p.
9. Mastylo, R., Dontsovb, D., Manske, E., Jäger, G., 2005, "A Focus Sensor for an Application in a Nanopositioning and Nanomeasuring Machine", Proceedings of the SPIE, Vol. 5856, pp. 238-244.
10. Minsky, M., 1961, "Microscopy Apparatus", US Patent 3.013.467.
11. Webb, R.H., 1996, "Confocal Optical Microscopy", Rep. Prog. Phys., Vol. 59, Issue 3, pp. 427-471.
12. Xi, P., Rajwa, B., Jones, J.T., Robinson, J.P., 2007, "The Design and Construction of a Cost-Efficient Confocal Laser Scanning Microscope", Am. J. Phys., Vol. 75, Issue 3, pp. 203-207.