Model Based Error Correction for Optical Aberrations in Laser Scanning Microscopes

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Abstract

In this article the use of an error correction strategy for optical aberrations based on ray-tracing is proposed and theoretically and experimentally validated using a laser scanning microscope of our own design. The system, its modelling and its calibration are briefly introduced together with experimental results. A comparison between the proposed error correction and one based on an artifact pre-measuring are also shown.

1 Introduction

Modern laser scanning microscope (LSM) designs are centred on conventional upright or inverted optical microscope arrangements and the use of complex objective lenses with high numerical apertures [1, 2]. These lenses are compensated so that they may work as near perfect optics, avoiding optical aberrations and deterioration of the system's performance. That comes with the price of large, heavy and costly optics with short working distances. Having in mind the computer power available nowadays, it is now possible to consider unconventional alternatives to optics optimization. By observing the optics as part of a complex system, it is possible to use simple optics and correct its optical errors computationally. With the use of simpler optics, weight and size can be reduced, raising system dynamics, reducing costs and facilitating the integration of scanning systems in different applications.

In this article the use of an error correction strategy for optical aberrations based on ray-tracing is proposed and validated using a LSM of own design [3].

2 System's Basic Structure

For evaluating the proposed error correction methods, a simplified LSM was designed [3]. It is based on the lateral scanning of samples through the deflection of a collimated beam with a 2D tilting mirror, and on a depth scanning through the displacement of the objective along the optical axis as shown in Fig. 1.

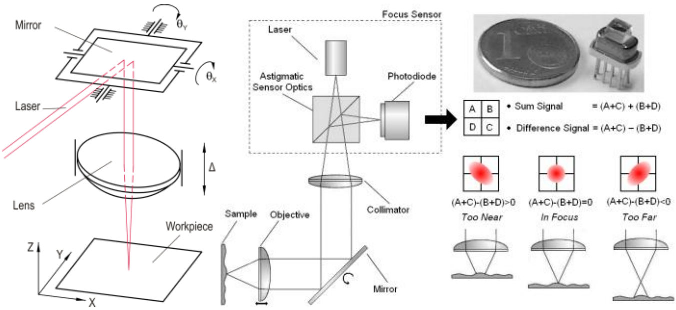


Figure 1: Scanning Microscope Basic Structure and Autofocus Procedure

The system uses a hologram laser unit as zero-sensor for an autofocus procedure [2, 3]. The autofocus is accomplished through the displacement 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. By keeping track of this displacement, 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.

3 Simple Optics and Ray-Tracing Modelling

Optical aberrations in uncompensated optics are systematic and as long as they can be modelled and predicted, they can be corrected. Ray-tracing offers a valuable tool for calculating these aberrations and is widely used in the design of compensated optical systems [2]. The purpose of this article is to show that it can also be used for the computer aided correction of aberrations in scanning systems.

Using ray-tracing together with kinematic chains to model the whole system, each triplet $\boldsymbol{x} = [\theta_x \theta_y \Delta]$ (Fig. 1) fully describes a state of the system and defines a unique focal point $[P_x P_y P_z]$ in the measuring volume. This way, the LSM can be seen as a mathematical function $F(\boldsymbol{x},\boldsymbol{Q})$ that relates kinematic and optical parameters ($\boldsymbol{Q}$) to 3D coordinate positions of the system focal point. This model, together with its calibration, is the basis of the proposed error correction strategy.

Considering the LSM as a function $F(\boldsymbol{x},\boldsymbol{Q})$, the system calibration consists basically in a problem of fitting a non-linear model to a set of experimental data.

Given the system's parameters $\boldsymbol{Q} = [\zeta_1, \ldots, \zeta_m]$, the function F can be differentiated, and the displacement of the focal point ΔP_i caused by an infinitesimal change $\Delta\zeta_i$ when the system is at a position $\boldsymbol{x_i}$ can be determined as:

$$\Delta P_i = [\Delta P_x \Delta P_y \Delta P_z] = \left(\partial F(\mathbf{x}_i, \mathbf{Q}) / \partial \zeta_1 \right) \Delta\zeta_1 + \ldots + \left(\partial F(\mathbf{x}_i, \mathbf{Q}) / \partial \zeta_m \right) \Delta\zeta_m \qquad \text{Eq. (1)}$$

The derivative shown in Eq. 1 can then be interpreted as an error equation of the LSM, where ΔP_i is the focus point position error when the system is at the position $\boldsymbol{x_i}$. However, this error can not be directly measured, so that, for calibrating the system, the problem must firstly be remodelled.

Using the set of parameters $\boldsymbol{Q}$ and a reference surface $\boldsymbol{S}$ described by the parameters $\boldsymbol{B} = [b_1, \ldots, b_n]$ a new function $F'(\theta_x\theta_y,\boldsymbol{Q},\boldsymbol{B})$ can be written to describe the necessary displacement of the objective to scan the surface $\boldsymbol{S}$. This displacement can be directly measured and the difference ε between the measured displacement (Δ) and the one obtained with F' is the model error. This way, the error equation can be rewritten in matricial form for different positions $\boldsymbol{x'_i} = [\theta_x\theta_y]$:

$$\varepsilon_i = (\Delta_i - F'(\mathbf{x}'_i, \mathbf{Q}, \mathbf{B})) = \left[\left(\partial F'(\mathbf{x}'_i, \mathbf{Q}, \mathbf{B}) / \partial \zeta_k \right) \quad \left(\partial F'(\mathbf{x}'_i, \mathbf{Q}, \mathbf{B}) / \partial b_t \right) \right]_{i \times (m+n)} \begin{bmatrix} \Delta\zeta_k \\ \Delta b_t \end{bmatrix}_{(m+n) \times 1} \qquad \text{Eq. (2)}$$

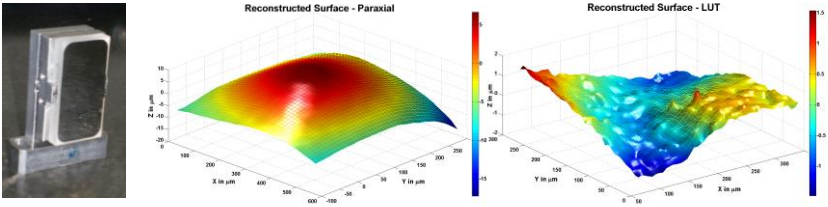
Using function F', the error ε_i in each position $\boldsymbol{x_i}$ is measureable and the calibration problem has been reduced to a non-linear problem of the type $\boldsymbol{Ax}=\boldsymbol{b}$. There is a great variety of methods to solve such systems. In this work the Levenberg-Marquardt algorithm was used [4]. It is a method that proved to be very successful in practice, especially in optical design.

4 Artifact Based Error Correction

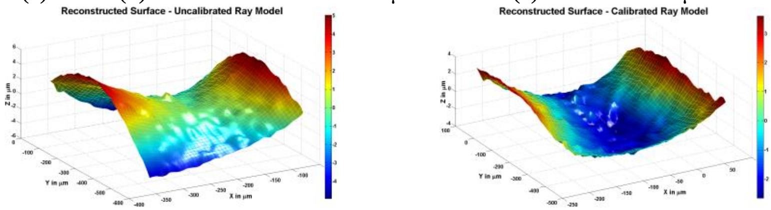
As an alternative to complex mathematical models, look-up-tables (LUT) offer a fast and direct method. Using a high quality (λ/20) plane mirror (Fig. 2a) as a reference artifact and considering it as a perfect plane, the influence of the optical aberrations on the system can be directly measured. Reconstructing the mirror surface with a simple paraxial model, the difference between the ideal plane and the measured data (Fig. 2b) can be interpreted as the measuring errors and a LUT can be built.

5 Comparison between Error Correction Methods

After the calibration of the ray-tracing model and the construction of the LUT, both methods were used to reconstruct a (λ/20) plane mirror in different positions. The observed surface deviations δ using a paraxial model, the calibrated and uncalibrated proposed ray-tracing model and the LUT are shown in Fig. 2.



(a) (b) Paraxial Model – δ ≈ 3.0µm (c) LUT – δ ≈ 0.7µm



(d) Uncalibrated Ray Model – δ ≈ 1.7µm (e) Calibrated Ray Model – δ ≈ 1.2µm

Figure 2. λ/20 Plane Mirror (a) and its measured surface using various models.

6 Conclusions

In this paper, the use of uncompensated optics in scanning systems was proposed in order to reduce weight and size and improve the dynamic behaviour of these systems. To avoid the influence of optical aberrations in the measurements a ray-tracing based correction model and its calibration were presented and compared with the results obtained using a look-up-table. The LUT showed slightly better results as it takes in account an average of all deviations in the system. The proposed model achieved similar results and, with the ongoing research, the calibration of its optical parameters (lens curvature, aspheric coefficients, etc.) will also be possible, improving even further its results. A combination of both methods also offers a promising alternative.

Acknowledgements:

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