Wavefront measurement based feedback control for automatic alignment of a high-NA optical system

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Abstract. Many applications of optical systems depend on focal spot quality, which depends on the alignment of the optical components. During alignment, it is difficult to monitor the spot quality because the spot position shifts with the alignment. This paper proposes to compensate for displacements of the focal spot and to monitor the spot quality by controlling the position of a Shack-Hartmann sensor. Low-order aberration data is used to control the position of a Shack-Hartmann sensor while higher-order aberrations are used to estimate focal spot quality. An experimental high numerical aperture setup is presented and the proposed method is applied. The experimental results successfully demonstrate the automatic alignment capabilities.

1. Introduction

Creating a focused spot of high quality by focusing a light beam is crucial for many applications, such as laser material processing [1] and high-precision optical displacement measurement [2]. However, the quality of the spot can be degraded by optical aberrations, for example due to manufacturing tolerances and non-optimal relative alignment of the optical components [3]. Optical aberrations can be measured by using Shack-Hartmann wavefront sensors, which are small and robust against environmental vibrations and can provide a high dynamic range [4]. In a Shack-Hartmann sensor (SHS), the entire wavefront is sampled by means of a microlens array (lenslet array) that creates spots on the image plane, where their position is recorded by an image sensor. From the measured spot patterns, the wavefront can be reconstructed using zonal or modal approaches [5]. This is routinely put into practice for flat or nearly-flat wavefronts [6]. However, in a focusing optical system - an example being a lens with high numerical aperture (NA) - the emerging wavefronts are closer to spherical wavefronts that converge towards the focal point and diverge afterwards. To use a Shack-Hartmann sensor to measure wavefront aberrations of converging or diverging wavefronts, an additional lens is needed to collimate the light to match the sensor aperture and reduce the wavefront curvature [7]. For non-optimal alignment, this lens introduces additional aberrations that impair the wavefront measurement.

In order to evaluate the quality of a focused spot, this paper presents an automatic lens alignment method that compensates for the above-mentioned aberrations with feedback control. To demonstrate the effectiveness of the method, this paper investigates the automatic alignment of a light source relative to a high-numerical-aperture (high-NA) lens. The alignment method is based on measuring the optical aberrations of the converging beam that is produced by

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the system under test for different positions of the light source to find the position with the smallest aberrations. The position-dependent aberrations introduced by the collimating lens are compensated by mechanical repositioning based on wavefront measurements.

Section 2 presents the details of how to automatically reposition the light source and the sensing unit using feedback control. An experimental setup for the automatic alignment of a light source and a high-NA lens is proposed and validated by experimental results in section 3. Section 4 concludes the paper.

2. Setup

The proposed measurement setup consists of a light source, a high-NA lens, a collimating lens and a Shack-Hartmann sensor (SHS) as shown in Figure 1.

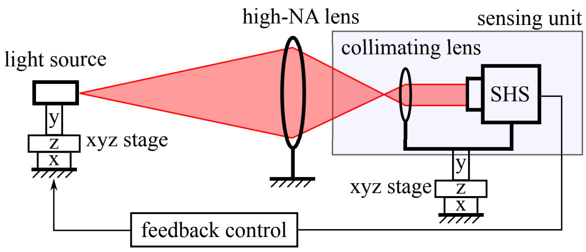

Figure 1. Test setup for measuring the aberrations caused by misalignment between a light source and a high-NA lens. The position of the light source is feedback-controlled to keep the focal spot on the optical axis of the sensing unit.

The light source and the sensing unit are mounted on motorized XYZ stages (VT-80, PI, Karlsruhe, Germany) to regulate their position with respect to the high-NA lens. Adjusting the position of the light source changes the position of the focal point with respect to the collimating lens. The collimating lens is sensitive to inaccurate optical alignment and introduces position dependent aberrations:

- A deviation of the focal point perpendicular to the optical axis of the collimating lens causes a collimated beam that is initially parallel to the optical axis to form an angle with the optical axis and consequently reach the SHS under an angle. This angle is detected by processing the focused spots on the image sensor of the SHS.
- A deviation along the optical axis changes the beam convergence/divergence and can be evaluated by calculating the distance between the spots on the image sensor.

These low-order optical aberrations due to inaccurate alignment superimpose the relevant optical aberrations to be inspected, i.e. aberrations caused by the high-NA lens and misalignment of the light source. To avoid these position dependent optical aberrations, tip-, tilt- and defocus-aberrations are actively compensated, as discussed in the next section.

2.1. Compensation strategy

The Shack-Hartmann sensor and the collimating lens are mounted on a motorized XYZ stage. They are moved all together to maintain their relative orientation. A modal reconstruction algorithm is used to find the coefficients of the Zernike polynomials by processing the spot pattern recorded by the SHS. The Zernike polynomials form an orthogonal base on the unit disk and within the paraxial approximation, they correspond to specific optical aberrations. The coefficients for tip and tilt are compensated in a closed loop by moving the X- and Y-stages,

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respectively. The Z-stage is used to keep the coefficient related to defocus-aberration below a threshold. In this fashion, the tip-, tilt- and defocus aberrations can be kept close to zero, which corresponds to accurate alignment of the collimating lens. Note, that these position-dependent aberrations can be compensated by feedback-controlling the position of *either* the light source *or* the sensing unit.

In the presented experimental setup, a higher precision is achieved by applying the feedback-control to the light source stages instead of the sensor stages. This is due to the optical configuration which provides a demagnification by a factor of six. For different optical configurations, the feedback-control is applied to the sensing unit instead.

3. Experimental results of the automatic alignment

For experimental evaluation, the sensing unit is moved to a number of positions on a 45x45 grid with 10 μm spacing. The light source is automatically repositioned by feedback control such that the tip-, tilt and defocus aberrations are below a threshold of 0.2. The first twelve Zernike coefficients and the light source position are acquired and recorded.

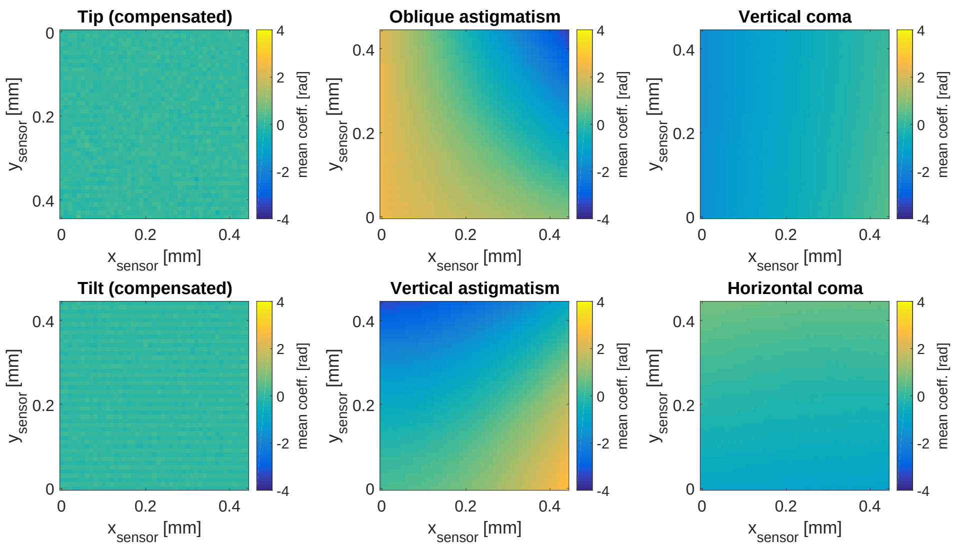

Figure 2. Six of the twelve recorded Zernike modes when moving the SH sensor by 10 μm increments along a 45x45 measurement grid. The left column shows the coefficients for tip and tilt, which are kept below a threshold of 0.2 by automatically repositioning the light source. The middle column shows astigmatism that strongly depends on the alignment. The right-most column displays the position-dependency of coma aberrations. Aberrations of higher order are not presented, as they are of smaller magnitude.

Figure 2 presents the recorded Zernike-coefficients, plotted against the sensor unit positions. It can be seen that the feedback controller moving the light source stages successfully compensates tip and tilt aberrations at all sensor positions. The middle column shows that astigmatism remains and depends on the alignment of the system. The sensor position also influences coma aberration, as shown in the right-most column of Fig. 2. The influence on higher order modes is not as pronounced and therefore not shown.

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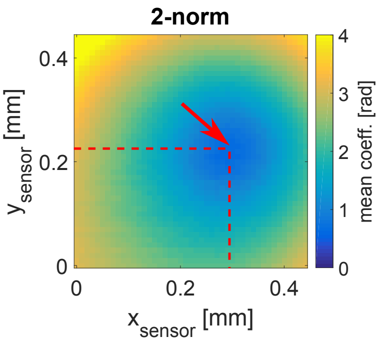

Figure 3. Recorded wavefront error map considering the first twelve Zernike modes. The norm is calculated as the square root of the sum of the squared coefficients. Experiment and labels are the same as in Figure 2. This error map indicates the light source position with the least overall wavefront aberrations (red arrow).

Figure 3 presents the resulting overall wavefront aberrations caused by the first twelve Zernike coefficients dependent on the sensor unit position. The 2-norm $= \sqrt{\sum_{i=1}^{12} Z_i^2}$ is used as a metric for overall wavefront-aberration (with the Zernike coefficients Z_i defined as in [7]). High-quality alignment is achieved near the center of the measurement grid, where the 2-norm is minimal (indicated by a red arrow in Fig. 3). The wavefront error at that position is smaller by a factor 7 when compared to the most aberrated position of the grid and 43% smaller than at the center position.

4. Conclusion

During the alignment of an optical system, the position of the focal spot shifts. This introduces position-dependent aberrations when monitoring the spot quality with a Shack-Hartmann sensor and a collimating lens. These detrimental influences of the collimating lens can be compensated by feedback-controlled repositioning of the sensor unit. The Zernike coefficients for tip-, tilt- and defocus-aberrations provide sufficient information for the feedback loop, while the remaining Zernike coefficients can be used to assess focal spot quality. In conclusion, the implemented procedure enables the alignment of the light source and the high-NA lens, improving the focusing quality by minimizing optical aberrations due to misalignment.

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