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Research Article

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Lens centering of aspheres for high-quality optics

Abstract: The assembly effort of optical systems can be reduced immensely by the use of appropriate manufacturing technologies. For refractive optical systems with a common axis of symmetry, lens centering allows a final system assembly with high accuracy and minimal effort, but is today mostly limited to spherical optical elements only. To overcome the current restrictions, a lens centering process for one-sided aspherical lenses was investigated both in theory and practice. The deviation of the rotational aspheric axis from a reference spindle axis is measured precisely with an electronic autocollimator and an additional distance sensor at the same time. Displacements can be minimized by a combination of lateral and rotational alignment motions, aiming at a coaxiality of both axes. In order to achieve a high performance of the entire optical system, the centered lens housings are machined with a diamond tool at their outer diameter, ground, and top surfaces. The feasibility of the complete process was proved by machining several aspherical lenses and measuring the final assemblies with a coordinate measuring machine. Thereby, a residual decenter <1 μm for the aspheric vertex and a tilt <0.5 arcmin between the aspheric axis and the axis of symmetry of the lens housing could be verified. The achievable manufacturing tolerances prove the practicability of the proposed lens-centering process for a majority of high-quality optical applications.

Keywords: alignment turning; aspherical lens; lens centering; lens system.

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1 Introduction

Aspherical optical elements became more and more important in a variety of areas of optical system engineering during the last years. In the field of reflective optical components, aspherical mirrors are already state of the art [1]. As a result of the progressive developments of molding technologies, computer-controlled grinding, and polishing, also aspherical lenses have reached a high level regarding form accuracy and roughness. Especially classical lens systems with a common axis of symmetry can benefit by the use of aspherical elements. Because of the reduction of optical surfaces in a lens system, its size and weight can be reduced dramatically, too. Therefore, cameras, microscopes, or measuring devices could be designed to be more compact and lightweight. In addition to that, aspheres allow an enhancement of the optical system performance by compensating specific aberrations.

Such an increase in optical performance is only accessible with high-quality optical components and an accurate mounting technology. Lens centering offers an effective and high-precision mounting of lens systems with a common axis of symmetry [2]. In the case of spherical lenses, lens centering has become a well-known process to compensate for residual position errors between a single lens or even doublets and their respective mounting. The high accuracies demanded are achieved through a combination of exact metrology, accurate alignment, and precise machining. Modern lens centering machines are, today, able to manufacture diffraction-limited optics even for the use in the DUV spectral range [3].

The increasing demand for aspherical lenses leads to a further development of the existing technology, particularly with regard to the metrology for determining the centering error. For that purpose, a lens centering process for aspherical lenses is presented in this paper.

2 Principles of lens centering

Basically, there are two main ideas to machine lens housings with reference to the optical axis of the optical element. One possibility is the fixation of the optomechanical assembly on an ultraprecision turning machine. The optical axis is measured absolutely in reference to the machine coordinate system, and the lens housing is machined by using servo tool technologies [4, 5]. Another approach uses an additional alignment chuck to adjust the lens with respect to the spindle axis of the turning machine. Because the axis is used as a reference, high-quality bearings that ensure a minimum of radial runout are required to achieve low final manufacturing tolerances. The housing is machined parallel and perpendicular to the spindle axis, manufacturing surfaces with high planarity. Figure 1 illustrates the principle of a lens centering process that uses the mentioned additional alignment chuck.

Independent of the particular technology used, both approaches are aimed at minimizing the centering error between the optical axis of a lens and its housing. A typical lens centering process can broadly be divided into the three sections centering measurement, alignment, and manufacturing. In the majority of cases, all sections have to be executed more than one time to ensure the required high-centering accuracies.

The centering measurement of spherical lenses to a defined reference axis is mostly carried out with an electronic autocollimator. Thereby, a collimated beam is focused on the optical surface under test in such a way that the reflected part of the light forms an autocollimation image at the image plane of the measuring device. By rotating the lens about the spindle axis, the series of images form a circle whose radius is proportional to the deviation between the center of curvature and the spindle axis. If the autocollimator is shifted along the spindle axis, the position errors of several optical surfaces can be determined [6]. In order to align the optical axis of a single sphere, it is sufficient to detect only the positions of the two centers of curvature from the front side and back side of the lens. Once the position of the optical axis is known, it can be adjusted with the help of the alignment chuck that allows a manipulation of the optical element in 4 degrees of freedom. The adjustment is carried out by introducing mechanical impulses generated with electromechanical actuators, achieving residual centering errors in the submicrometer range [7, 8]. Finally, the aligned assembly is machined with precision tools that ensure slight cutting forces and low final surface roughnesses. Diamond tools fulfill these requirements for typically used materials like brass or aluminum. The outer diameter of the lens housing defines its radial position in the optical system. By turning the ground and end surfaces, the air distances between the single lenses can be adjusted precisely.

Lens centering reduces the final system mounting to a simple drop-in assembly with high precision and minimal effort. The required tolerances for every single lens clearly depend on the application of the optical system. However, one should always keep in mind that aspherical lenses usually come with tighter tolerances compared to spheres because the decentering of aspheres mostly degrades the final image quality more strongly than equivalent spherical elements [9]. Table 1 depicts typical assembly tolerances of spherical and aspherical lenses for high-quality optical systems, such as microscope objectives or high-end camera lenses.

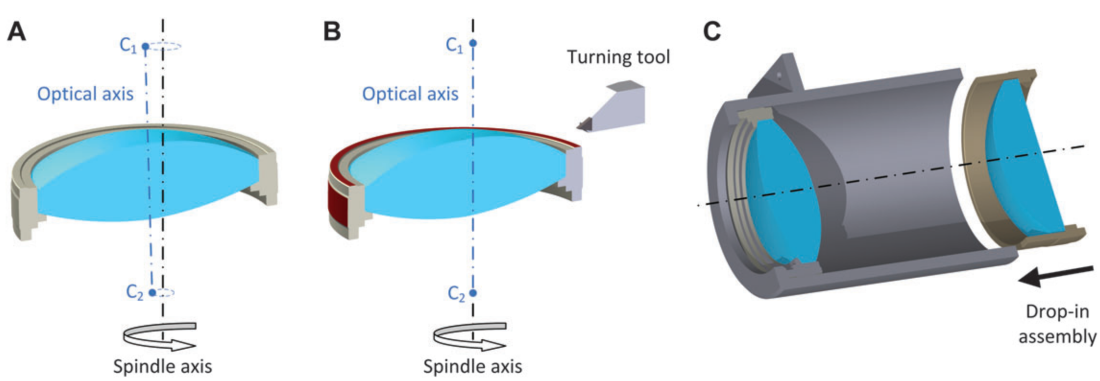

Figure 1 Principle of lens centering: (A) after mounting the lens on the machine, the centering error of the sphere is determined by measuring the runout of both centers of curvatures C_1 and C_2 with an electronic autocollimator. The error is compensated by shifting and tilting the optical axis onto the spindle axis of the turning machine. (B) Afterwards, the housing is machined at its reference surfaces (red) parallel and perpendicular to the optical axis, achieving coaxiality between the optical axis and the symmetry axis of the lens housing. (C) The final system mounting is reduced to a simple drop-in assembly along the common symmetry axis of the optical system. No further alignment is required.

Component Tolerance	Consumer optics (spherical lenses)	HQ-optics (spherical lenses)	HQ-optics (aspherical lenses)	Micro-optics for photonics
Single lens				
Tilt error	<±5 arcmin	<±30 arcsec	<±10 arcsec	<±30 arcsec
Lateral decenter	<±50 µm	<±10 µm	<±10 µm	<±1 µm
Axial displacement	<±50 µm	<±10 µm	<±10 µm	<±1 µm
Lens group				
Tilt error	<±30 arcsec	<±30 arcsec	<±10 arcsec	<±30 arcsec
Lateral decenter	<±50 µm	<±2 µm	<±10 µm	<±1 µm

Table 1 Typical assembly tolerances for high-quality (HQ) optics (according to [9]).

3 Centering measurement of aspherical lenses

As mentioned above, the centering of spherical lenses is controlled with an electronic autocollimator by measuring the deviations of both centers of curvature from a defined reference axis. Regarding aspheres, an additional tilt of the rotationally symmetric surface has to be considered. An electronic autocollimator is able to detect only the decenter of the paraxial center of curvature of the aspheric surface. In order to align the surface according to its axis of symmetry, a supplemental point sensor is used to measure the relative distance to the aspheric surface near the outer edge of the lens [10]. Figure 2 illustrates the machine and measurement setup with the most important components.

An accurate alignment of an aspheric surface implies the correct interpretation of the measured signals. The position of the paraxial center of curvature is evaluated with the help of the electronic autocollimator as described in the previous section. A more demanding task is the evaluation of the measured signal from the point sensor. It will be influenced by a lateral decenter and a tilt of the aspherical axis related to the spindle axis. Thus, it can be described as a superposition of two sinusoidal signals. In order to align the aspherical surface, both parts have to be separated. Therefore, the shape of the specific asphere and the lateral measuring position of the distance sensor have to be considered. Incorporating all this information, the portion of the lateral displacement to the sinusoidal wave can be calculated. This is possible because the autocollimator detects the relative position of the paraxial center of curvature of the asphere with submicrometer accuracy. The calculated signal is subtracted from the measured signal to obtain the part of the aspherical tilt. Amplitude and phase are evaluated to achieve an absolute value for the angle between the aspherical axis and the spindle axis.

Even if the measurement principle appears comparatively simple, it allows the detection of centering errors of almost every one-sided aspherical lens, whether it is convex or concave, has a small or large diameter, or comes up with high departures from the spherical shape. Another advantage of the used measurement principle is the possible detection of the center of curvature from the backside of the lens. Owing to manufacturing limits, there is a wedge error between both optical surfaces. The centering error of the second surface can be measured in the traditional way to permit an alignment not only for the aspherical surface but also for the entire lens with a minimal centering error appropriate to the specifications of the optical design.

Besides the numerous advantages of the measurement principle, there are also some limitations that have to

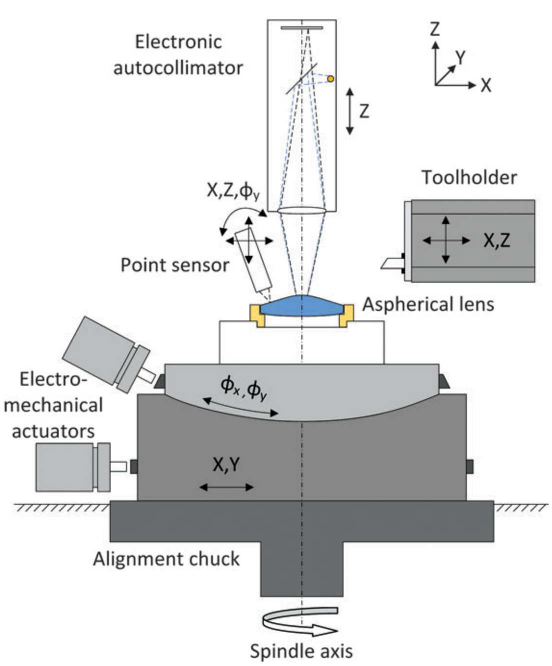

Figure 2 Machine and measurement setup: The lens is mounted on the alignment chuck. The autocollimator measures the lateral decenter of the paraxial center of curvature from the top. The distance sensor is adjusted in three DOF to measure perpendicular to the aspheric surface. Diamond tools are installed on a toolholder at the opposed side.

be considered. Aspherical surfaces with small deviations from the spherical shape are much more difficult to align. Because slight form deviations lead only to small measured amplitudes, the detected signals are in the range of the measurement uncertainty of the distance sensor. In addition to that, parameters like lens imperfections, measurement uncertainties of the electronic autocollimator, and the point sensor or a positioning error of the sensor have an impact on the centering measurement. These differences from the ideal measuring conditions affect either the amplitudes or phases of the measured distance signals, or even both of them. Their influences can be minimized by an accurate positioning of the measurement devices and a statistical evaluation of the measured centering error.

4 Alignment and manufacturing

Subsequent to the centering measurement, the lens is aligned in reference to the spindle axis of the turning machine. Because of the possible moving directions of the alignment chuck, there are a few potential strategies to adjust the aspherical surface. In order to reduce the necessary alignment time, it is most feasible to initially correct the lateral decenter. Afterwards, the tilt between the aspherical axis and the spindle axis is compensated, always considering the residual decenter that could not be eliminated in the prior correction cycle. Following this procedure, the lens is usually aligned in a few iterations, resulting in an overall alignment time of mostly <3 min.

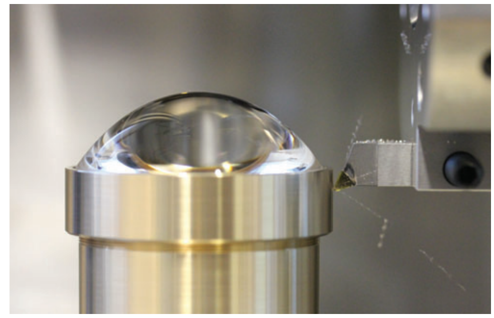

Figure 4 Diamond turning of the outer diameter of a lens housing.

During the alignment process, the lens position is controlled either with the electronic autocollimator or the distance sensor, which allows a permanent feedback of the current residual centering error. Figure 3 illustrates a typical alignment procedure on the basis of the measured signals. In this case, an asphere with a diameter of 52 mm and a maximum deviation of about 700 μm from the best fit sphere was aligned. After mounting the lens on the turning machine, the initial measured tilt was calculated to 512 arcsec with an additional lateral decenter of approximately 49 μm. The exemplary asphere could be aligned automatically within 3 min and two iterations only to a final lateral measured centering error <0.3 μm for the decenter and 10 arcsec for the tilt, respectively.

Finally, the aligned lens housing was machined with a diamond tool at their outer diameter, ground, and top surface as can be seen in Figure 4. To verify the coincidence of aspherical axis and axis of symmetry of the lens

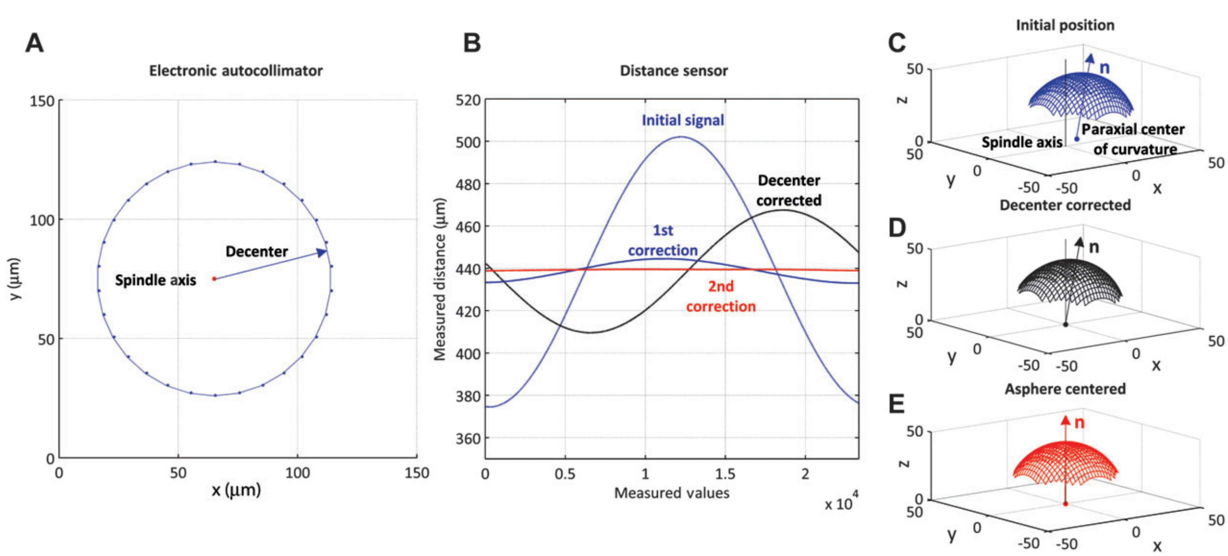

Figure 3 Measured signals during an alignment: The initially shifted and tilted asphere (C) is first aligned in the lateral direction so that the paraxial center of curvature coincides with the spindle axis (D). As a result, the initially measured circle (A) degrades into a point, and the measured distance signal (B) changes in amplitude and phase. Afterwards, the residual tilt is corrected in two more correction cycles to center the aspherical lens (E).

Parameter	Tolerance
Alignment	
Lateral decenter paraxial center of curvature	<0.3 μm
Tilt aspherical axis	<15 arcsec
Alignment after manufacturing	
Lateral decenter aspheric apex to axis of symmetry lens housing	<1 μm
Tilt aspherical axis to axis of symmetry lens housing	<0.5 arcmin
Lens housing	
Diameter	<2 μm
Cylindricity	<0.5 μm
Flatness plane surfaces	<1 μm

Table 2 Achievable tolerances for one-sided aspherical lenses.

housing, the manufactured assembly was measured with a multisensor coordinate measuring machine. This measurement permits a comparison between the original CAD model and the actual manufactured lens by calculating the difference between both data. The asphere was measured 100 times with a touching probe and an optical sensor on more than 100 points over the entire geometry, while the optical surface was defined as the measurement reference. In the software, a plane was fitted to the measured points at the upper flat surface of the lens housing and a cylinder to the points measured at the circumference. The angle between the normal vector of the plane and the aspherical axis is mostly influenced by the residual tilt, which could not be eliminated during manufacturing. A comparison of the positions of cylindrical and aspherical axes allows the determination of a residual lateral lens decenter and also proves the measured tilt error. Table 2 summarizes the generally achieved production tolerances for all investigated aspheres, while the given values refer to an alignment according to the aspherical surface only.

5 Conclusion and outlook

The attainable tolerances prove the feasibility of the proposed lens centering process for aspheres, especially for lenses with high departures from the spherical shape. All investigated aspheres could be aligned in <3 min to a final alignment accuracy of <0.3 μm for the decenter of the paraxial center of curvature and to 15 arcsec for the tilt between aspherical axis and spindle axis. After machining the lens housings, values for the decenter <1 μm between aspherical apex and symmetry axis of the housing and a residual tilt <0.5 arcmin were generally achieved. Differences in accuracy between alignment and manufacturing are due to possible influences of the alignment chuck during the turning process, while the given values always represent the worst case. In most cases, centering accuracy is maintained completely during manufacturing.

However, even if the manufacturing tolerances enable applications of lens centering of aspheres for consumer optics and also for a majority of high-quality optics, there is still future work that has to be done to fulfill the requirements of applications that demand tighter centering tolerances. This implies an improvement of the centering measurement particularly with regard to the influence of lens imperfections and the investigation of alternative measurement principles. Besides a further development of lens centering for aspherical lenses, the manufacturing of defined reference surfaces on other optical geometries, like cylindrical optics or prisms, will be the focus of interest.

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