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# Effective optical system assembly by ultra-precise manufactured references

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**Abstract**
As demonstrated in the present work, exact manufactured references play a crucial role in order to effectively assemble high-quality optical systems. Based on the experience of alignment turning of spherical and aspherical lenses, the approach can be transferred to non-rotational symmetric elements like prisms, active components (e.g. laser diodes), and freeform mirrors. Depending on the complexity of the optical component, on-machine metrology or specific measurement setups have to be used to determine the position and orientation of the references with respect to the optical function. The resulting correction data is taken into account of the machining process. The following correction cycle realizes mounting and metrology references down to sub-micron precision with diamond machining techniques. This approach allows for a predictable and passive system assembly of demanding optical systems and even freeform arrangements. Different machining setups as well as the corresponding metrology approaches are shown. Results are given for representative components. The effectivity of the approach is discussed on example of a Snap-together freeform mirror system.

Keywords: optical system assembly, reference structures, alignment turning, Snap-together

## 1. Introduction

The quality of optical systems strongly depends on the exact and long term stable positioning of the optical elements along the beam path. Expenses for assembly work can easily escalate with the number of elements and degrees of freedom (DOF) that have to be aligned (refer table 1). The increasing use of aspheres and freeforms in high-quality optical systems requires for deterministic and time saving assembly processes. Ultra-precise manufactured references and mounting structures that correspond to the optical axis of the individual optical element can be favorably used for fast and reliable system integration. So called "Drop-in" or "Snap-together" techniques [1] aim at the consequent utilization of diamond machined mounting structures in tight relation to the optical axis of the component.

**Table 1.** Degrees of freedom (DOF) to be aligned in system assemby

| Optical surface | Number of DOF | DOF |
|---|---|---|
| Plano | 2 | Rx, Ry |
| Sphere | 3 | Rx, Ry, (Tx, Ty), Tz |
| Asphere | 5 | Rx, Ry, Tx, Ty, Tz |
| Freeform | 6 | Rx, Ry, Rz, Tx, Ty, Tz |

## 2. Methods

The basic principle relies on an ultra-precise machining of references and mounting surfaces to generate an exact relation between the optical and the mechanical coordinate systems (cf. figure 1). For traditional circular symmetric optics, e.g. spherical or aspherical lenses, the coordinate transfer is achieved by diamond turning the rotationally symmetric lens housing in order to guarantee for a maximum coincidence between optical and mechanical axes [2]. The optical axis is determined by an on-machine metrology and is either aligned with an adjustment support to the turning spindle or considered as input data for a servo turning operation, whereby a tilted cylinder toolpath with respect to the optical axis is used for machining. The alignment turning approach is able to realize tolerances regarding decentration, socket diameter and vertex height of less than 2 micrometers. During the subsequent assembling operation, all alignment turned lens subassemblies are passively filled in a tube with a tight clearance in the micrometer range.

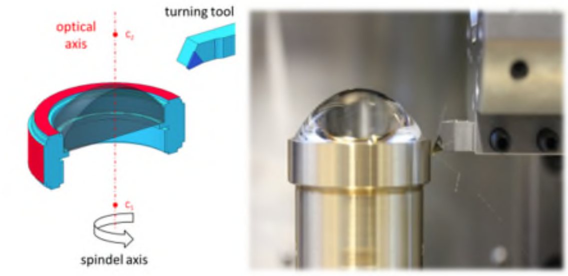


**Figure 1.** Left: machining of references (red) parallel and perpendicular to the optical axis; right: alignment turning of an asphere

Non-rotational symmetric components like beam splitters, sensor devices, or light sources are widespread in arrangements that require for complex adjustment mechanisms. Following the approach of alignment turning for rotationally symmetric optics can be used in order to implement diamond milled reference planes and a platform oriented and simplified assembly technique (cf. figure 2). According to the optical function of the element, the determination of cutting correction data is carried out by adapted metrology setups. In case of beam splitter components, a combined transmittive and reflective electronic autocollimator setup can be used to gain information about the tilt of the optical beam with respect to the mechanical references. A reproducable clamping during machining and metrology can be reasonably realized using a zero point clamping system. Typical angular accuracies in Rx, Ry, and Rz realized by the diamond milling correction cycle are less than 10 arcsec.

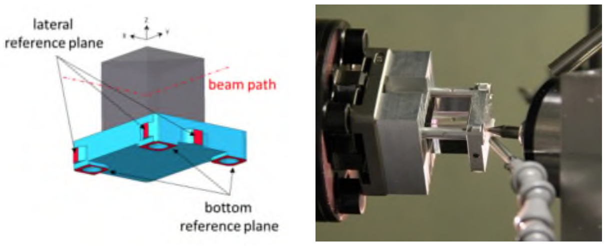


**Figure 2.** Left: prism with carrier and references; right: micro milling of reference structures

The approach can be extended to freeform metal mirrors by a sequential machining of optical and mounting surfaces at the mirror body in the same machine setting (cf. figure 3). By deploying a manufacturing related optical design, further simplifications can be obtained by modularizing two optical surfaces and machining them mechanically coupled on a single platform. Comparable to the "Drop-in" of an alignment turned stack of lenses into a precise tube, fabrication of high-quality interfaces at the mirror bodies and at the telescope frame reduces the considerable degrees of freedom and lead to a passive system assembly strategy.

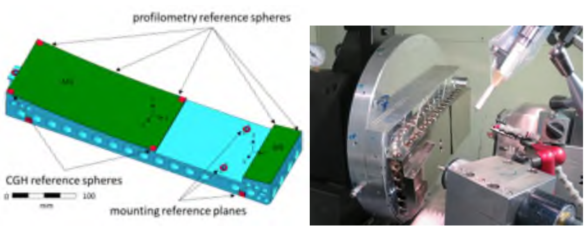


**Figure 3.** Left: freeform mirror module with reference structures; right: diamond milling process on a ultra-precision lathe

### 3. Snap-together freeform telescope

The research was carried out on a four-mirror anamorphic imaging telescope for the visual wavelength range (cf. figures 4, 6). Due to the usage of 4 freeform mirrors, 24 critical DOF have to be basically considered for the system alignment. The arrangement of each two mirror surfaces on a common mechanical platform reduces the number of DOF to 12. Diamond machined mounting flats and stops fix any other DOF excepting Tx, Ty, and Rz of one module for the fine alignment with respect to the second one.

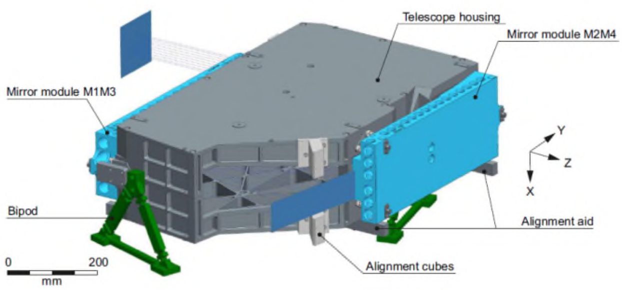


**Figure 4.** Opto-mechanical design of the Snap-together freeform telescope

The developed maching setups are shown in figure 5. The fast tool servo module realizes the optical freeform shape on a conventional T-axis lathe configuration. An additional milling module, working in X-Z-C-mode, machines the fiducials for metrology and assembly processes. A fly-cutting process was used for the planarization of the telescope housing as well as for adjusting the Z-distance in-between the mirror platforms. All critical dimensions were checked with a tactile probing coordinate measurement machine with the following accuracies:

- flatness of mounting interfaces: < 1.5 µm
- parallelism mounting interfaces: 8 arcsec
- angularities: < 5 arcsec
- length tolerance of mounting interfaces: about 5 µm (> 380 mm length)

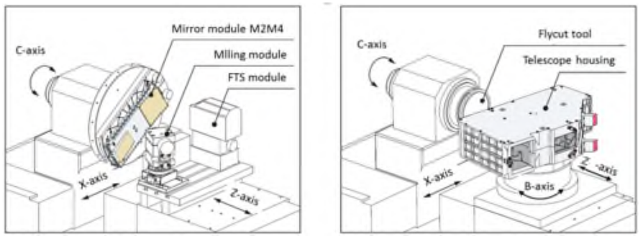


**Figure 5.** Machine setups for reference manufacturing

After correcting the mirror surface form deviation with Magnetorheological finishing (MRF) and a following smoothing step by roboter polishing, the Snap-together assembly at the diamond machined interfaces were performed. The system wave aberration could be measured directly after the initial assembly. The final fine adjustment under interferometric control has been done within a few iterations. The desired diffraction limited performance @ 633 nm was reached over the entire field of view.

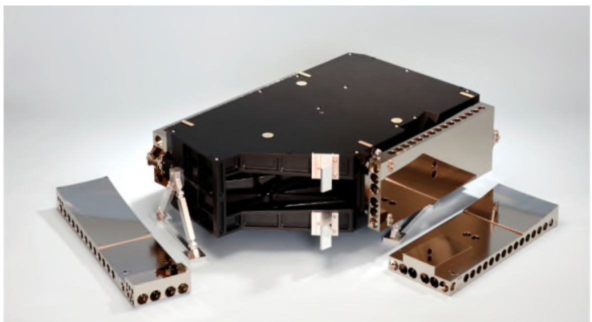

**Figure 6.** Telescope breadboard for VIS applications

### 4. Conclusion

The proposed manufacturing approach puts high efforts into the manufacturing of individual optical components. At the same time, it leads to great advantages in the later system assembly step. The most essential point is a consequent referencing of the optical coordinate system throughout the whole manufacturing chain. The transfer of a simplified alignment and integration approaches is demonstrated for large freeform mirrors in the VIS.

### 5. Acknowledgements

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