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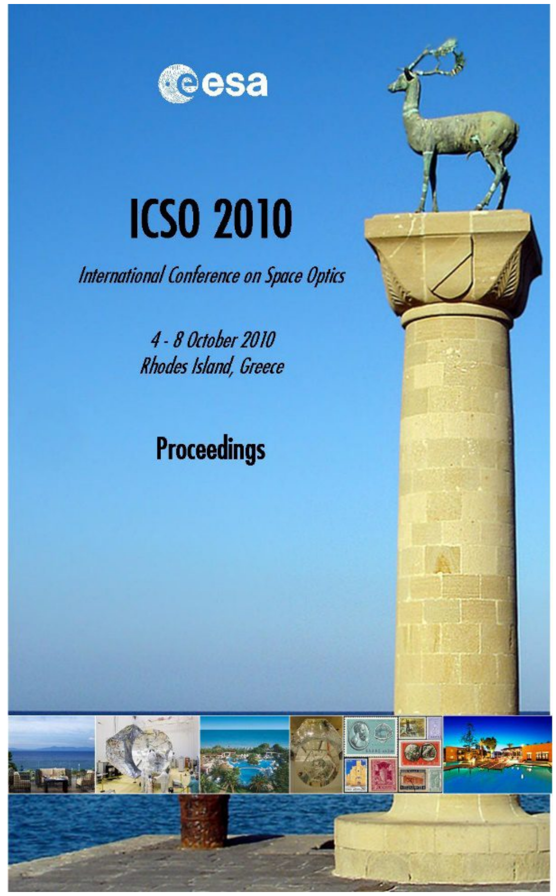

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FREEFORM DESIGN AND FABRICATION: WHERE THE PROOF OF THE PUDDING IS IN VERIFICATION

M. D. Nijkerk, O. E. van der Togt-Marinescu, G. P. H. Gubbels.
TNO Science and Industry, Stieltjesweg 1, 2628 CK, Delft, The Netherlands

I. INTRODUCTION

A freeform optical surface is typically defined as any surface that does not have an axis of rotational symmetry. These surfaces provide additional degrees of freedom that can lead to improved performance compared to systems that make use solely of conventional optics. The benefits of using freeforms are:

- Less optics can be used in the opto-mechanical system and therefore a decrease in the amount of optical surfaces occurs. Since every surface is a reduction of light intensity (e.g. by scattering), a higher throughput of the optical system is the result.
- Less optics also means a reduction in mass and size
- An improvement in optical quality (e.g. spherical aberration, coma, distortion)
- A more favourable position of the optical components is possible

Generally, these freeform surfaces are more difficult to manufacture, and therefore more expensive both in cost and in development time. Furthermore, there is a danger with the application of exotic freeforms that have a large number of parameters, and consequently, degrees of freedom. For the latter reason they may naively seem attractive from the point of view of an optical designer, providing many knobs to optimize the performance; however, the overwhelming number of parameters may also cause a hotchpotch of local optima in merit function landscape. Many of those will not lead to an improved design because e.g. the particular freeform representation does not provide the correct handles, or the location in the optical train is unsuitably chosen. Another difficulty in the application of freeforms is the complexity of describing and evaluating the surface form tolerances of non-symmetric surfaces.

Yet another difficulty is the following. An appropriate conventional design can often be obtained as an optimization from a paraxial system that can be defined analytically. For instance, both the telecentric beam expander and the push broom telescope that will be described in more detail below, can be derived from standard optical rules. Then, the paraxial design is a good starting point for an optimization algorithm as is used in optical design software in the hunt for an optimum design. In contrast, for a design that includes non-symmetric optics, the parameters that provide the departure from symmetry are not so easily obtained with an analytically determined first guess. This makes it difficult to coax the optimizer into the right direction.

Thus, with the benefits of using freeforms come disadvantages:

- Difficult to determine the optimal freeform representation and location in the optical train
- Optical tolerance analyses are not yet common practice in optical design packages
- Difficult to manufacture with classical production technologies
- Difficult to validate the surface shape
- More difficult to align, because of the increased degrees of freedom
- For all of the reasons above: more expensive

Consequently, optical designers sometimes are hesitant to apply free form surfaces in an optical design difficult as they are to handle both from design and manufacturability of point of view.

At TNO, we are involved in the total chain of design, tolerance analysis, manufacture and test, and that must also include freeform designs. For manufacturing, we have at our disposal a freeform diamond turning machine, and for materials that can not be diamond turned, we can apply computer controlled deterministic polishing. For the metrology, which is just as important as the manufacturing step, we use the newly-developed non-contact freeform metrology instrument NANOMEFOS [1]. For tolerancing, we use the most versatile features in the CodeV optical design software [2], to address specifically those surface imperfections that we can expect from the used manufacturing technologies.

From a practical point of view, any surface that is not manufactured with classical production technologies can also be considered a freeform surface, simply by nature of the non-symmetric fabrication process. Although not all disadvantages linked with application of freeforms apply, the aspects of manufacturing, tolerancing and validation and cost do play a role.

In the following sections, we will addresses some of the bullets in the list of disadvantages by describing two case studies from space optics: a refractive beam expander for a laser guide star system and a push broom telescope. Both are currently being manufactured at our facilities.

II. FREEFORM ENGINEERING APPROACH

Despite the ongoing trend of fabrication of freeforms, the experience in their application in high tech optical systems is relatively limited. As a result, the design and engineering approach when applying freeform elements is a little bit different compared with conventional optics.

In Fig. 1 a possible block diagram of freeform engineering is shown. In the upper left corner, an abridged scheme of designing is shown. Starting off with a paraxial design, analytical investigation of the performance could lead to fruitful inclusion of freeform degrees of freedom. Subsequently, a tolerance analysis provides input on the manufacturability. Note that here we are mainly concerned with surface shape tolerances and will disregard mechanical and alignment tolerances. On the lower right, the chain for freeform manufacturing and metrology is shown. The latter includes measuring steps, to be performed with e.g. NANOMEFOS, that are used to provide information for (corrective) deterministic polishing and single point diamond turning (SPDT) steps.

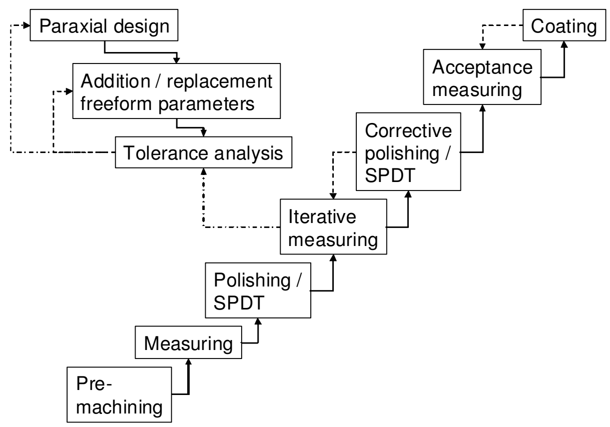

Fig. 1. Design and fabrication flow of non-conventional optics

A. Freeform Application in design

It is not trivial to lay out rules of thumb on how to improve a design by adding freeforms, but one helpful approach is to consider the ray aberrations locally in the field or pupil and to imagine what manipulations of the surface would be needed to counter those aberrations.

For illustrative purposes, a very simple case that greatly benefits from abandoning spherical optics is an off-axis small field optical relay. In Fig. 2, a point A is imaged to a point B off-axis. When using a spherical mirror the system will suffer a lot of aberrations. One can imagine that it is possible to manipulate the aberrated rays in order to converge better in point B, and that the way to do this is to locally adapt the power and apply a displacement.

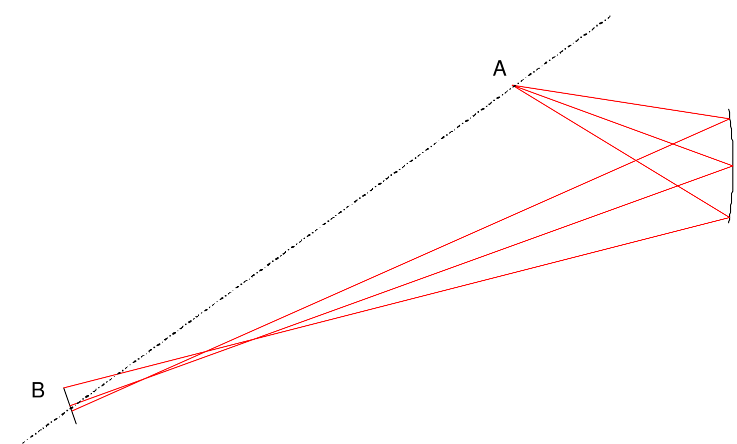

Fig. 2. Optical relay with aberrations

In this simple case it is not difficult to understand that error-free imaging can be realized with an off-axis conic. The axis of rotation is indicated with the dash-dotted line in the figure.

B. Freeform tolerances

A connection arrow from the fabrication scheme to the design scheme indicates the link between the fabrication method and the tolerance analysis. During optical design, the sensitivity of the performance with respect to errors in the surface shape are determined using standard tolerance or sensitivity analysis tools of the optical design software. Due to the nature of the manufacturing step, with conventional optics it is typically sufficient to regard regular and irregular power fit or sagitta error with respect to the nominal test sphere. These can directly be included as a tolerance in the optical design software. Regular and irregular power errors can be considered as a special case of "periodic" surface shape errors with a period on the order of half the size of the work piece, the direction of periodicity being radial or linear, respectively. The amplitude of the periodic error is then related to the number of fringes on the test plate fit.

In contrast, with non-conventional fabrication steps like deterministic polishing or SPDT, surface shape errors with a smaller period can be expected. The period, direction of periodicity and amplitude depend strongly on the fabrication step. Obviously, the surface shape error can assume a more random nature as well. For now, the random nature will be ignored.

In Fig. 3, an example of a freeform mirror, fabricated with SPDT is shown. The mirror is actually an ordinary sphere, but as part of a pilot study, it was turned off-axially: the axis-of-rotation of the work piece during fabrication did not coincide with the axis of the sphere. The work piece has a length of about 140 mm. The radius of curvature is on the order of 200 mm.

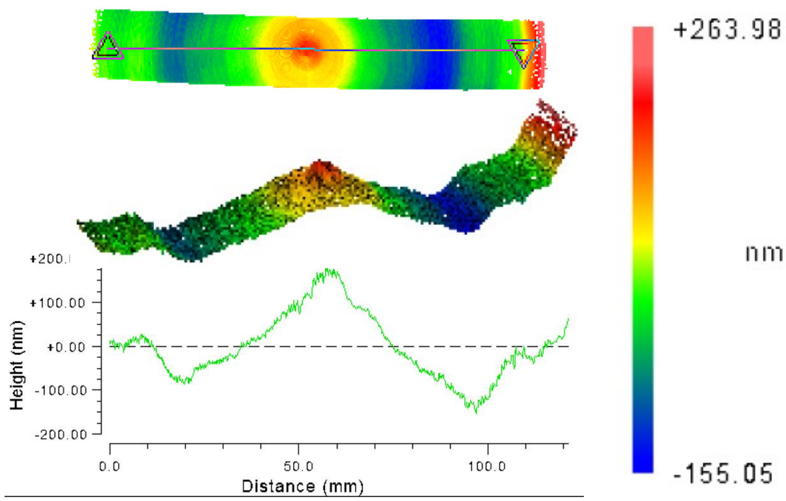

Fig. 3. Off-axis sphere processed by diamond turning, first run, no iteration performed

The off-axis sphere was measured on a Zygo profilometer. Colour contour plot as well as a line scan are shown. It must be stressed that this is the result of a single diamond turning step. The mirror has undergone no iterative refinement. This first effort serves to illustrate the type of surface shape errors one can expect with non-conventional fabrication techniques. The peak-to-valley surface sag error with respect to the best fit sphere measured 419 nm, the rms surface sag error measured 73 nm. This first run shows a concentric periodic surface shape error, with two periods over the long dimension of the work piece.

The influence of this surface shape error on e.g. spot size performance can not be assessed with the standard tooling in CodeV. To expand on the capabilities, we utilized the feature of user defined surfaces. The sag of the mirror surface, including shape tolerances, is described as the addition of the nominal shape and a surface error. The periodic surface error can be represented in terms of a cosine function. For other fabrication processes, different shapes may be more appropriate.

In Fig. 4. the periodic surface error is exemplified. In the top figure, a radial periodic error is shown. In the bottom figure, a linear periodic error is shown.

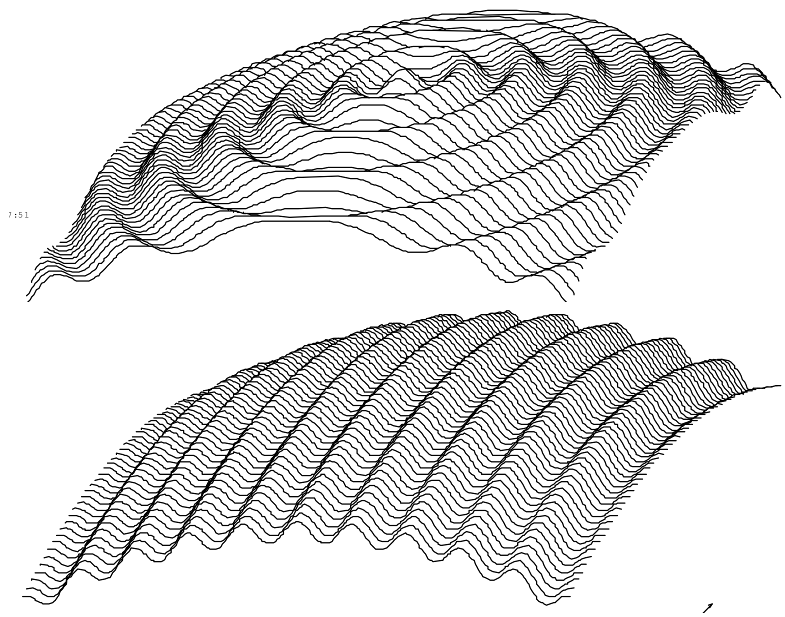

Fig. 4. Non-conventional surface errors as modeled in CodeV

The radial and periodic error are applicable to different diamond turning strategies, slow servo tooling, when the diamond chisel spirals over the work piece, and XZC machining, in which the work piece rotates, the axis of rotation moves in one direction perpendicular to the axis, and the chisel moves in the direction parallel to the axis, respectively. In the latter method, work piece is a body of revolution. The off-axis sphere shown above is machined with the slow servo tool option.

Note that CodeV has the option in tolerance computations to apply a concentric cosine shaped ripple to a surface, but this option can only be used for standard performance measures like wavefront error. For more flexible performance measures used in user defined tolerancing, the method shown here must be applied.

III. CASE STUDY: PUSH BROOM TELESCOPE

The Ozone Monitoring Instrument OMI [] contains a push broom telescope with a wide field of view, sweeping over the earth surface with global daily coverage. The telescope [] combines an unsurpassed wide field of view (114°) with high image quality. The two-mirror telescope has a pupil and an intermediate image in between the mirrors and images an elongated swath on the earth surface on a spectrometer slit, the image being telecentric. Both mirrors are simple spheres. The demands on pupil location, telecentricity, distance between the mirrors and desired magnification define the paraxial system. The image quality of the OMI telescope is such that a several km square region at Earth's surface can be resolved from an 820 km orbit. The layout of the OMI telescope is shown in Fig. 5.

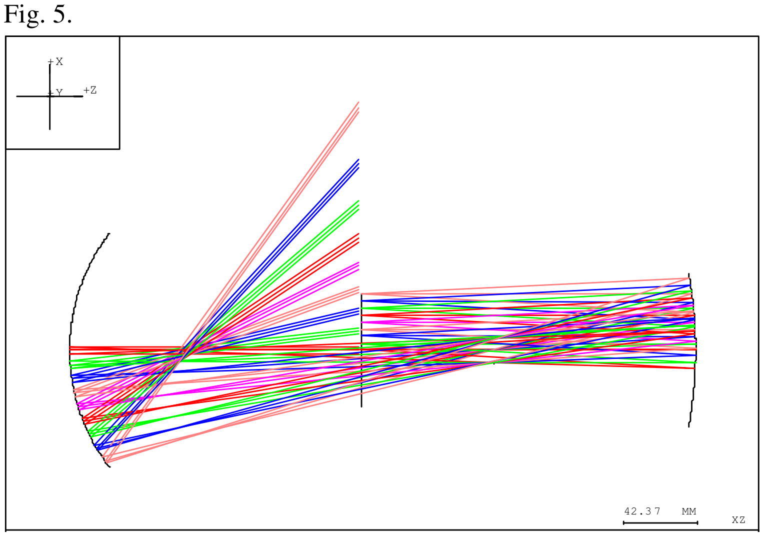

Fig. 5. Layout of OMI telescope

The successor of OMI, TROPOMI (Tropospheric Monitoring Instrument) [] contains a push broom telescope with a paraxial system identical to the system of OMI, but by applying freeform mirrors, the image quality could be improved by more than an order of magnitude. The TROPOMI telescope is almost diffraction limited.

The secondary mirror (right in Fig. 5) is an x-toroid, i.e. a body of revolution obtained by rotating a conic curve in the xz plane about an axis parallel to the x-axis. The curvature in xz and yz direction differ, thus enabling an anamorphotic system. The primary mirror is an adapted x-toroid, in which the local curvature in the x-direction gradually varies in the y-direction. The primary mirror effectively resembles a rectangular part of a sphere surface onto which a torsion is applied, twisting one long end of the rectangle up and the other long end down. The long end of the rectangle lies in the x-direction.

The secondary mirror has a conic constant. When looking at the system from slit to earth, the parameters of the secondary mirror are optimized such, that extra aberrations are introduced in the intermediate image, which can rather accurately be countered specifically by the aforementioned shape of the primary mirror.

TROPOMI is scheduled to launch in 2014 and bread board studies are underway. The off-axis sphere shown in Fig. 3 is a manufacturing trial that is representative for the primary TROPOMI mirror. The trial helps us to investigate the possible surface shape errors and set up the tools for tolerance analysis. The choice of implementing the surface errors using user defined surfaces provides practically unlimited flexibility in the performance criteria. The surface error shown in the figure leads to an image degradation of only a few tens of percent, thus the telescope is forgiving for surface tolerances.

Mirrors for a bread board TROPOMI telescope are being manufactured by TNO. Surface measurements will be performed using NANOMEFOS, and the measurements will be used for iterative corrective diamond turning steps. At the time of writing, no new results are available for presentation.

IV. CASE STUDY: REFRACTIVE BEAM EXPANDER FOR LASER GUIDE STAR

TNO is involved in building a laser guide star system. The laser guide star is a reference beacon for adaptive optics []. It is obtained by illuminating the sodium layer in the mesosphere at 80 – 100 km altitude. The laser guide star system contains an afocal refractive beam expander which optically resembles a Galilean telescope. The Galilean telescope has a small negative lens and a large positive lens. This is an example of a system that follows from a relatively simple paraxial description. In order to meet the desired performance however may require abandoning conventional spherical optics. The laser guide star is close to the diffraction limit of the optical system. In reference to the altitude, this points to a primary lens diameter of several tens of cm. The large primary convex lens has one conic surface that serves to minimize spherical aberration. Notably due to its sheer size, this lens can be considered a freeform, since it cannot be manufactured using conventional techniques. The primary lens will be fabricated using deterministic corrective polishing. The input for deterministic polishing will be provided by NANOMEFOS.

Bonnet size and polishing profile lead to surface deformation that can be modeled in CodeV with periodic surface errors, implemented with user defined surfaces. Representative test measurements provide information on the required structure of the user defined surfaces, that can subsequently be used in tolerance analyses. The advantage keeping the tolerance analysis close within the iterative loop of measurement and deterministic polishing is that it gives confidence that after alignment, the optical system performs according to specifications and will not need additional corrective steps. In this manner, expensive and time-consuming alignment steps can be kept to a minimum.

V. CONCLUSIONS

TNO is involved in the total chain of design, analysis, fabrication and metrology of freeform and aspheric optics. In this paper we have illustrated some of the steps in this chain. Two cases were described that rely on two different manufacturing methods that can be applied to freeforms: diamond turning and computer controlled deterministic polishing. Both cases are actual projects that are being carried out at TNO facilities at this time.

The design can be a straightforward improvent of a paraxial design by including higher orders, as is effectively the case for the afocal telescope. On the other hand, it can be a intricate interplay of balancing the aberrations of two elements in the optical train, as is the case for the push broom telescope.

Tolerancing optics that are not manufactured in the conventional way relies on good knowledge of the fabrication technique. Trial samples provide input for expected surface errors, that can be implemented by describing surface including errors in terms of user defined surfaces. This gives high flexibility in addressing specific performance measures, and allows a close interaction with the fabrication process, which helps in reducing the need for intermediate assembly and subsequent corrective steps.

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