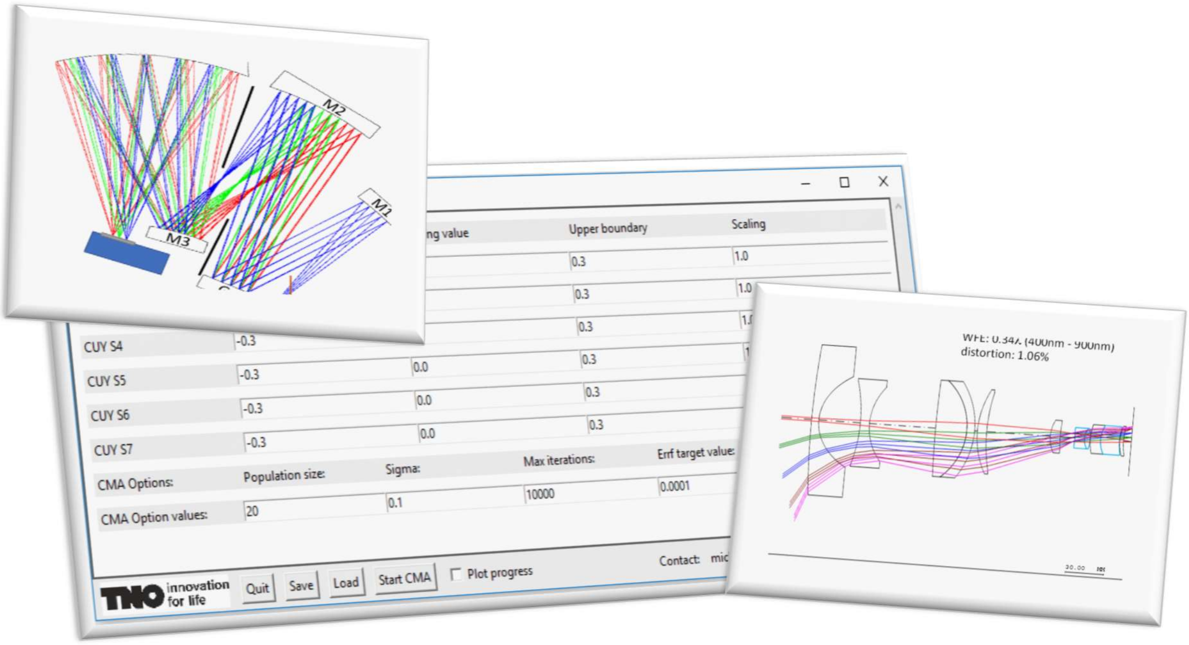
Design Tools and Alignment Concepts for Free-Form Optics



Executive Summary Report

	Name	Date	Signature
Prepared by	David Nijkerk	1-12-2017	
Reviewed by	Michael Gruber	4-12-2017	
Approved by	Bart Boonacker	4-12-2017	

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1 Scope

This document is the executive summary of the "Design Tools and Alignment Concepts for Free-Form Optics" project, conducted by TNO and subcontractor Inria. It describes the summary of the major technical challenges and accomplishments of the contract by ESA (Contract No. 4000118002/16/NL/BJ/gp).

The work has been performed by TNO and subcontractor Inria between September 2016 and December 2017.

1.1 References

1.1.1 Applicable Documents

	Document	Reference	issue
AD-01	ESA project contract & SOW	ESA Contract No. 4000118002/16/NL/BJ/gp	1
AD-02	TNO final report	FFO-TNO-FR-001-i1 Final report	1

1.1.2 Reference Documents

Ref.	Title

2 Executive Summary

2.1 Context

For next generation space missions optical instruments need to be compact, lightweight and cost-effective, but should show a higher performance in terms of optical performance, stability and robustness at the same time. Solutions can be found by using free-form optics, as demonstrated e.g. in the telescope of the TROPOMI instrument.

With the advent of new developments in optical manufacturing technologies, such as single point diamond turning, opto-mechanical systems are no longer limited by the shapes realizable by manufacturing, but by the solutions proposed by the optical designers. Freeform design is a game changer drastically altering the structure of the commonly used optical design software and free-form surface descriptions, that are leading to inefficient usage of the potential of these surfaces to define compact, high performance system configurations.

Next to insufficient mathematical free-form surface descriptions and design methods, free form optical surfaces add considerable complexity to the MAIT phase of the instrument development. This project addressed the issues that are related to free-form optics during design and development of space-based instruments.

2.2 Project objective and team

The overall objective of the project is to enable the use of free-form optics in future space missions instruments by developing a novel design tool and identifying best alignment and test strategies.

The following additional objectives are explicitly mentioned in the Statement of Work [AD-01]:
1. Define the baseline mathematical description of free-form surfaces;
2. Define procedure and best practices for optical design using free-form components;
3. Demonstrate advantage of the developed free-form design tools on two case studies;
4. Develop alignment strategy and test methods with accuracy compatible with the two case studies

These goals reflect new facets and challenges in the design and application of free-form optics.

The activity was led by TNO and subcontracted part of the development of a state-of-the-art computational optimization technology to Inria. TNO has been developing space optical instruments for over 50 years. TNO worked on free-form optics for more than 10 years, amongst which is the state-of-the-art free-form telescope of TROPOMI. Inria is the French institute for Computational Science and Applied Mathematics and the creator of the CMA-ES algorithm, currently considered as one of the best non-linear optimization algorithms available.

2.3 Methodology

The project was executed in four phases, 1) a review of state-of-the-art in order to benefit from the latest developments in free-form optics, 2) a review and baseline definition of the requirements for the development and demonstration test cases, 3) the development of the optimization tool and 4) the demonstration of the optimization tool by executing two test cases.

During the first phase the state-of-the-art of free-form optics was investigated. The investigation focused on three topics; mathematical representation of free-form surfaces, free-form optics for space applications and optical design methods.

From the state-of-the-art review the ingredients for the free-form optics optimization (FFOO) tool have been collected into a baseline concept. The concept tool incorporated the most promising global optimization algorithm CMA-ES. Also, the tool was required to cope with different free-form surface representations in order to represent the best solutions for the two test cases.

During the third phase the optimization algorithm CMA-ES was implemented into the FFOO tool and coupled with the commercial optical design software CodeV. The selected mathematical representations of the free-form surfaces were already implemented in CodeV and could be used directly.

The FFOO tool was demonstrated by the execution of two test cases in the fourth and final phase of the project. The first test case consisted of a wide FOV lens with very challenging image quality and distortion requirements. An imaging spectrometer with state-of-the-art requirements (on some parts comparable to TROPOMI) was selected for the second test case. Due to the importance of MAIT in the free-form optics design process, tolerance analysis, alignment and test methodologies have been developed for the two cases.

2.4 Results

A fully functional FFOO tool was developed during this project which combines the CMA-ES global optimization algorithm with the CodeV software for the raytracing of the optical systems and for the calculation of optical parameters (wavefront error, distortion, smile, keystone etc.). The best of both worlds are combined into one single tool.

The implementation of CMA-ES turns the FFOO tool into a robust optimization tool which is capable of jumping over, in other words dismissing, optical configurations that are not ray-traceable. This is one of the most important shortcomings which are encountered with CodeV optimizations. Additionally, the FFOO tool provides the freedom to use the CMA-ES optimization in conjunction with other promising design methods such as direct construction, analytical designs or alternative surface implementations, that bridge the phase between paraxial design and starting configuration.

The wide FOV lens test case resulted in multiple designs due to the different interpretations of the distortion requirement (equidistant or equilateral distortion). For both distortion types the FFOO tool provided results which are not as good as compared to the CodeV optimization. This is because of the vastly advanced error functions present in CodeV built on *a priori* knowledge of the nature of the merit function. However, given the *a priori* knowledge, the CodeV design is not much better than the FFOO tool which provides a lot of freedom to include available knowledge.

For the imaging spectrometer the FFOO tool optimized results were significantly better than CodeV results in similar conditions in terms of time frame, merit function construction and starting point. The FFOO Tool is capable of optimizing bad starting points while Code V global synthesis cannot handle this and requires a locally optimized starting points. Additionally, the FFOO Tool can be used in combination with alternative design methods (Delano approach for instance) that are outside of the scope of Code V.

Implementing tolerances for both test cases lead to a performance degradation as expected. For both test cases, almost all optical surfaces can be measured using normal interferometric setups or NANOMEFOS, with the exception of two lens surfaces. For the test cases the alignment methodologies are described, based on a lens barrel with cylindrical housings for the wide FOV lens and on precision milled mechanical reference surfaces and dowel pins for the spectrometer alignment..

2.5 Conclusions and Recommendations

The developed FFOO tool enables the use of free-form optics in optical design. It has been demonstrated that the FFOO tool can be used for two very different and extremely challenging space optical systems. For complex design cases the FFOO tool performs better than existing commercial optical design software. For design cases where *a priori* knowledge of the merit function is available the FFOO tool is not as good as existing commercial optical design software.

Due to the highly flexible nature of the tool and optimization algorithm, the FFOO tool can be employed for many different space instrument designs. For this, the FFOO tool can be used in combination with alternative design methods (Delano approach for instance) that are outside of the scope of existing commercial optical design software.

The benefits of the FFOO tool for different system designs such as a catadioptric design configuration was briefly touched upon in the final report [AD-2]. The FFOO tool can be expanded further to include more/different design methods. The first recommendation is therefore to extend the functionality of the FFOO tool to new design configurations in order to optimize the potential of the FFOO tool for future free-form optics systems.

While the implementation of some surface representations are not fully adopted in the free-form optics community there remains a blanket of uncertainty what these “extreme” (in numbers of DOF and local definitions) surface representations could bring. The second recommendation is therefore to investigate the potential of these surface representations.

The current study did not focus on the manufacturability of the free-form optical surfaces. While there is currently sufficient knowledge on manufacturing free-form optics surfaces, the requirements are becoming ever more stringent (thereby increasing cost). The third recommendation is to initiate research on the optimization of free-form optics surfaces for manufacturability, e.g. to optimize for “low-cost” free-form optical surfaces. This relates not only to free-form surface shape, but also to requirements on mid-spatial frequencies, roughness and shape/sag errors.