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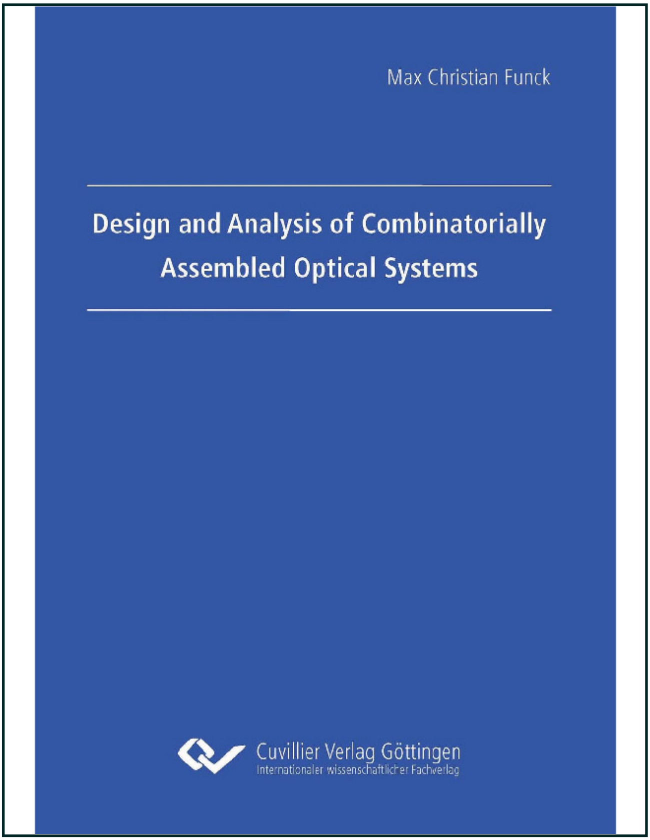
Design and Analysis of Combinatorially Assembled Optical Systems



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1 Introduction

Optical systems and instruments are synonymous for high precision, performance and quality and the requirements to guide light to a sharp focus are indeed very demanding. In terms of geometrical optics, the distance any two rays travel from an object point to an image point must agree within a quarter of the wavelength of light*. In the visible 100 nm is the limit, while for extreme ultra violet light, used in the latest semiconductor technology, the limit is reduced to a few nanometers.

Like only few other countries Germany has a long and successful history in developing and producing high performance optical systems. This focus has remained till today and companies are concentrating on small to medium quantities of specialized and customized products. The specialization is made possible by a large number of skilled designers and engineers but also due to competition from countries with low labor cost. Of all the produced optical systems the largest share in sales volumes is reported for innovative applications in production technology, metrology and life science [OPTE07].

The demand for precise optical instruments is expected to rise even further. This is supported by the observation that optical devices are shrinking in size, that wavelengths and light pulses are getting shorter and that the amount of information transmitted by optical systems is steadily growing [HERI06]. At the same time, however, and as optical systems are increasingly part of consumer products, drastic price and time demands develop. It has long been identified that solutions enabling cost-efficient production of high performance optical systems in small to medium quantities need to be developed in order to stay competitive on the global market [SIEG02].

Three factors with a large impact on performance and cost of optical systems can be identified: optical design, component manufacture and assembly. As with most developments, a large fraction of the cost is determined in early design stages. With respect to high performance systems, the design choice determines not only the nominal performance but also the sensitivity to manufacturing tolerances. Tight tolerances mean high costs and in order to deal with tolerance induced performance degradation assembly of high-quality optical systems relies heavily on compensation strategies such as alignment. The development of optical systems hence exhibits a large amount of manual

* According to the Rayleigh criterion describing diffraction limited performance and distance referring to the optical path length [RAYL79].

assembly, making assembly a costly and often time consuming production step. Automation does not play a significant role because the produced lens designs change frequently and because assembly procedures requiring iterative adjustments are slow and difficult to automate [BECK05]. As a consequence, the optical industry is facing one of the dilemmas of production: highly specialized and complex small scale production with the need for scalable production technologies that enable the exploitation of economies of scale [SCHU07].

It is the goal of this work to contribute to solving this problem by investigating the application of a non-iterative assembly method which can compensate tolerance effects during the production of high-quality optical systems.

The work targets lens designers and optical engineers, providing the necessary tools to analyze and evaluate the applicability in early design stages as well as methods to successfully develop suitable optical systems. Most importantly, the performance of optical systems as a function of optical design, manufacturing tolerances and assembly method must be accurately predicted such that a cost-benefit analysis can be conducted.

1.1 State of the art – Developing high performance optical systems

Imaging optical systems have been designed and developed for a very long time, first through experimentation and crafting later by deliberate mathematical design. Calculation is based on Snell's law of refraction and the law of reflection which is sufficient for most applications as long as the finiteness of the wavelength can be neglected [BORN99]. Approximations of geometrical optics, explaining aberrations, the deviation of rays from perfect point imagery, made first performance increases possible.

The most important aberration theory is credited to Seidel [GROS07]. But more advanced theories for higher order errors [BUCH68] and asymmetric deviations exist [THOM80]. Since the 1980s the use of personal computers has further increased design performance. Following the works of Baker and Feder [FEDE62] computer-based optimization of a weighted error function (merit function) combining optical performance and boundary conditions is employed to maximize the performance. The merit function *MF* describes the weighted (w_i) difference of a design expressed by design functions f_i of parameters $\underline{x}$ to an ideal system state [GROS07].

1.1
$$MF(\underline{x}) = \sum_i w_i \cdot \left[\tau_i - f_i(\underline{x})\right]^2$$

The merit function contains targets τ_i for aberrations as well as first-order properties and boundary conditions such as geometrical restrictions. Sometimes the merit function is normalized by the sum of the weights.

Minimization of the merit function optimizes the performance and is based on nonlinear search algorithms including steepest descent, conjugate descent, Damped Least Squares (DLS) and Newtonian methods, finding local optima in the vicinity of a starting point [SMIT92]. Locating the global optimum of the merit function is an ongoing subject of discussion [KUPE93] and many optical design programs have implemented proprietary solutions. Algorithms are based on stochastic starting points, evolutionary and genetic search or simulated annealing [BASS09]. A systematic method to locate all different local optima by generating saddle points and subsequent local optimization with DLS is proposed by Bociort et. al. [BOCI05,VTUR09].

Despite the heavy use of computers to calculate and optimize optical systems, lens design is sometimes regarded an art [SHAN97]; only few design methodologies exist and they are rarely reported on. Intuition, experience and sometimes trial and error appear to dominate the development process to a large degree. As a consequence, optical systems are rarely developed from scratch. More typical, especially in longstanding companies, existing designs are modified and adapted to new specifications. Basis for these developments are lens databases, the patent literature or company own solutions. Haferkorn is among very few people describing a systematic process of optical system synthesis [HAFE84].

In addition, lens designers developed design strategies that make systematic use of aberration theory that may even be used to generate start designs for computer optimization. The design process can be divided into four stages: design choice, determination of powers and materials, shape adjustment and reduction of residual aberrations [SMIT00]. Kidger uses aspherical surfaces during preliminary design and suggests starting with monochromatic aberrations before correcting chromatic aberrations [KIDG01,KIDG04] while Shafer highlights the importance of aberration theory and aplanatic and concentric surfaces [SHAF80]. The methods are experience-based and general guidelines. Designing optical systems requires control over dozens of variables and even with today's optimization programs no design procedure surely leading to optical systems of the desired performance exists.

While optimal design performance is very important, the actual performance of optical systems is largely determined by manufacturing and assembly tolerances. Thanks to sophisticated tolerance analyses, the performance and yield of assembled systems can be accurately predicted. The importance of such analyses and careful tolerance assignment has grown immensely. Smith describes how deviations based on wavefront changes can be summed up to form a worst case or statistical estimate [SMIT85]. Adams provides statistical methods to predict the tolerance effect based on Gaussian tolerance distributions, including compensation [ADAM87]. Older publications develop analytical tolerance analysis models to reduce computational effort [KOCH78,PINT80]. Today, sensitivity analysis, Monte Carlo analysis and differential ray tracing analysis are the most important types [PERI05].

Traditionally, optical system design followed a strict sequential procedure: system layout, lens design and optical engineering [KING83]. While the system designer laid out the entire project and took account of specifications and cost, the lens designer refined the optical design before the optical engineer would assign tolerances, prepare drawings of mechanical parts and initiate manufacture and purchase.

Realizing the importance of tolerances on performance and cost, design for manufacturing strategies have emerged [KIDG04]. The strategies are mostly best-practice rules. Optimizing the optomechanical design to reduce tolerance effects [MARG99] and cost optimal tolerancing [YOUN01,WILL92] are some of the more systematic approaches. Including tolerance sensitivities in the optical design optimization is a major step towards an integrated product development. It aims at reducing the cost and increasing the robustness of a lens during design rather than finding a mechanical design that will enable the system to work [GREY70,YOUN06].

While the optical system design procedure has become more intertwined, the number of technical disciplines involved in the design process has also increased. This is because today's optical systems are characterized by a close interaction of optical, mechanical and often electronic components as well as an increased number of manufacturing alternatives [BLIE08]. As a result, the development process is often highly iterative and changes in the different phases result in a process of adaption that is dominated by the correct analysis of tolerances, environmental influences and their impact on system performance. Recently, simulation tools for the analysis of optical systems are brought closer together. Computer-aided design of mechanical parts is being connected to optical simulations and finite element analyses of structural and thermal behavior is combined with ray-tracing calculations to further increase performance [DOYL02].

Assembly, comprising the steps of joining, handling, alignment, test and additional processes is frequently one of the most important and costly production steps and responsible for a large fraction of added value [LOTT06]. This is particularly true for precision assembly with complex assembly routines. Of the different assembly steps, compensation is of particular interest for precision manufacture and very common in optics. Compensation is the ability to reduce errors induced by a set of parameter perturbations by (another) set of parameters.

Classical compensators in optical systems are air spaces and centration of lenses or lens groups to adjust symmetrical and asymmetrical aberrations such as on-axis coma, spherical aberration or distortion [GROS07]. Less frequently, rotation of lenses (clocking) is used to reduce on-axis astigmatism [GROS07]. Other errors can be compensated if parameters are measured prior to the assembly and air spaces or curvatures re-optimized [SCHL96]. Common examples include adapting a system to measured radii or glass melt data.

While adjustments moderately increase cost and require additional mechanical elements, reworking designated surfaces does not, but is only considered for very high-performance lenses [SCHL96]. Other related methods include centering of lenses and assemblies in mechanical cells using lathe centering or automated bonding [BLIE08]. Interferometric characterization and subsequent adaptation of the computer model to yield measured results can be used to iteratively adjust parameters [STEP89].

With increasing complexity, systematic selection of compensation parameters becomes more important. The selection can be based on sensitivity analyses of Zernike polynomials decomposing the wavefront into orthogonal polynomials [GROS07] that are suitable to measure compensation. Chapman and Sweeny find the most effective set of compensation parameters through singular value decomposition (SVD) of the design parameters' second derivatives [CHAP98].

Selective assembly is an assembly strategy used to improve quality and reduce costs and is based on measuring and sorting components (or subassemblies) into tolerance groups and selecting parts of matching groups for assembly [WARN96]. Selective assembly can be used to employ otherwise non-adjustable optical parameters such as lens curvatures as compensators.

Kidger describes the selective assembly of toroidal surfaces during the combination of achromatic doublets [KIDG04]. Application is also described by Ray [RAY02] who suggests the combination of suitably deviating components for the assembly of photographic lenses as well as by Thorburn [THOR83] and Haferkorn [HAFE84]. Adams states that tolerance analysis of selective assembly is still an open question in optical tolerance analysis [ADAM87] and Kingslake points out that a large number of lenses is required for what he calls matching [KING78].

Recently, Latyev et al. have published a study on the selective assembly of microscope objectives [LATY09] and [LATY10]. Research focuses on the adaptive and selective assembly method, developed by Zocher [ZOCH85] featuring a feedback loop into component manufacture and optimization of tolerance classes [GÖRS99] to avoid mismatch.

To summarize, non-iterative compensation methods which are most suitable for automation are rarely applied to optical systems. Infrequently, selective assembly is employed to increase performance but the usability for small quantities is limited and the method is not widely accepted. Multiple reasons can be identified:

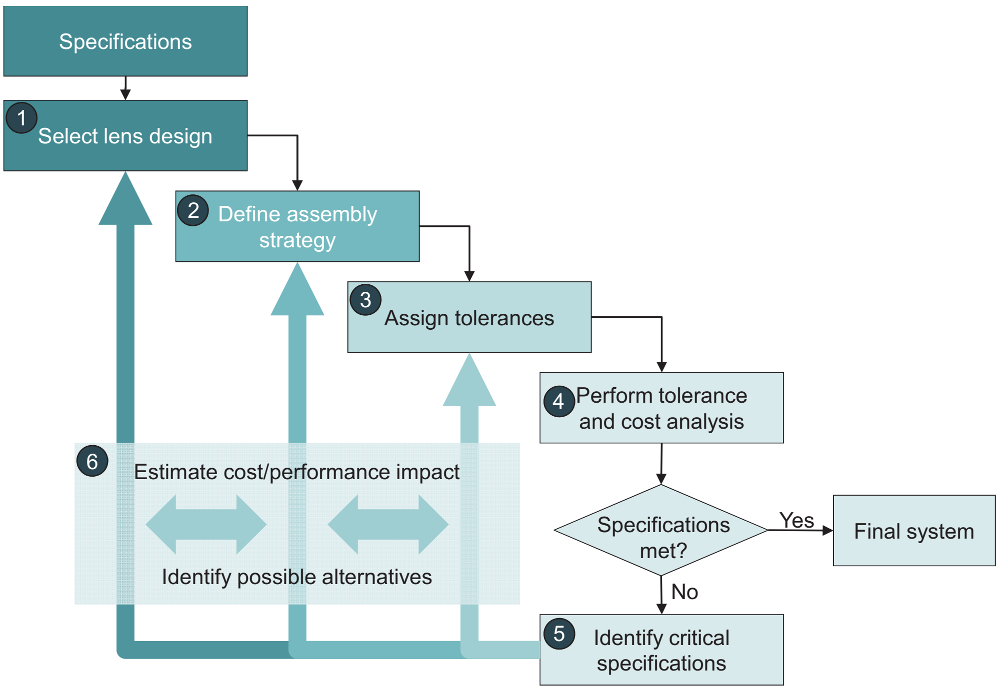
- The method is not systematically conducted, but applied in a trial and error manner as described e.g. by [RAY02]. As a consequence, the performance increase remains uncertain.
- Interrelations between system parameters in optical systems are sometimes complex and require delicate and precise compensation of multiple parameters. Selective assembly is perceived as a strategy limited to simpler problems not suitable to solve optic-specific needs.
- A tolerance analysis concept for selective assembly, predicting the as-built performance does not exist. Hence, optical engineers do not know how to tolerance a design for selective assembly and cannot estimate a possible cost benefit.
- Lens design methods considering compensation methods are lacking. Most designs are therefore unsuitable for selective assembly and the full potential of selective assembly remains unused.

1.2 Goal and outline

In order to resolve the issues pointed out in chapter 1.1, the general idea of selective assembly will be taken up in this work but modified to better suit the needs of optic development. Instead of classifying components into tolerance groups, components are individually combined. Such individual component selection is unknown in the optics literature but is regarded a formidable solution for smaller production series and interrelated performance functions. In order to distinguish the method from selective assembly, the term combinatorial assembly is used hereafter.

The goal of this dissertation is to develop combinatorial assembly as a systematic method and employ it in the best possible way in order to facilitate cost-efficient production of high performance optical systems. Finding a cost-efficient approach during the conception and design of an optical system generally requires an iterative approach (Figure 1) that breaks up the traditional sequential development sequence.

Figure 1
Iterative development approach for optical systems



Based on given performance specifications a lens developer will derive an initial design and proceed to selecting an assembly strategy before he defines tolerances and analyses the performance (step 1-4). In a first trial, assembly without compensation and a simple set of tolerances will be tested. If cost or performance requirements are not satisfied, critical specifications are identified and possible changes discussed (step 5). Evaluating different options in the next step (step 6) is a classical engineering process based on intuition, experience and a good amount of systematic trial and error. After changes in lens design, assembly strategy and tolerances have been decided on the process starts again until a satisfactory result is obtained.

While the iterative approach is very generally applicable, this work expands the possibilities of the lens developer. New is the possibility to employ combinatorial assembly as an alternative assembly strategy (step 2) and analyze a systems performance with a specific tolerance analysis (step 4). New is also that combinatorial assembly requires an integrative discussion of its application as well as lens design and tolerance changes (step 6).

One of the goals is therefore to provide lens designers and optical engineers with suitable tools and knowledge to elaborate the application of combinatorial assembly. This requires the development of a systematic method to apply combinatorial assembly as well as simplified models, tolerance analyses and design methods.

Following a brief introduction to manufacturing tolerances, their effects on optical system performance as well as methods to analyze and assign tolerances this dissertation will

- develop the principle of combinatorial assembly including a formal description of the selection process. Different optimization methods delivering optimal component combinations are implemented, compared and their potential applications stated (chapter 3.1 and 3.2)
- formulate a systematic approach to selecting optical components for combinatorial assembly (chapter 3.3).
- expand tolerance analysis methods to predict the performance of combinatorially assembled systems and strategies to assign tolerances (chapter 4)
- contribute design methods to find optical designs optimized for the application of combinatorial assembly increasing possible error compensation and reduce tolerance requirements (chapter 5).

Finally, applications of combinatorial assembly are presented in chapter 6. The examples are carefully chosen to demonstrate the versatility of combinatorial assembly and its benefits in reducing errors of different orders.