Visible imaging system optical design by continuous optimization of glasses

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Abstract. Choice of lenses materials in optical design is crucial to reduce aberrations down to an acceptable level. Commercial glasses do not cover a continuous range of refractive indices and must be selected in a discrete library making them discrete variables in any optimization design process to achieve the final optical design to be manufactured. This paper proposes an alternative method to avoid the complicated discrete variables optimization process thanks to a two-steps continuous optimization methodology starting with fictitious glasses models before jumping to the real glasses optimization design. The illustration of this process and achieved results are presented on an example of optical system which validates our proposed method.

1 Introduction

Optical design of systems comprising refracting lens elements involves optimization of tens of continuous variables describing the system geometry and of other parameters such as glasses. The latter can be described as discrete variable thus requiring the use of mixed optimization strategies that are able to deal with a mixture of continuous and discrete variables. However, the most commonly used optimizers in the optical domain (e.g. Levenberg-Marquardt, Pseudo-second-derivatives, proprietary algorithms [1]) are only tailored to geometrical –continuous- variables [2]. Efforts have been made to overcome this challenge including the addition of new functionalities (see glass expert in Code V [3]) or the addition of genetic algorithms able to handle mixed optimization [4]. On the one hand, commercial software functionalities do not cover the entire glasses database. On the other hand, most mixed optimization algorithms are today not robust enough against the heavily noisy optical error functions in presence of more than 10 lens including several asphers.

The present work introduces the methodology we have developed as an intermediate way to optimize glasses choice. It is illustrated in rotationally symmetrical refractive system in the visible through the use of successive continuous optimization steps. So far, it has been tested in the visible range where method assumptions (described in 2) are valid. Our strategy is broken down into the following steps:

1. Continuous optimization of geometrical parameters together with fictitious materials models parameters.
2. Selection of materials from a minimal distance between fictitious material parameters and real materials parameters.
3. Re-optimization from formerly optimized geometry and selected real materials.

The continuous optimization strategy is the same as the one presented in ref. [5].

2 Method

There are two leading assumptions to this method:

A. Any visible material can be uniquely characterized by 3 parameters \((n_e, V, \Theta_{g,d})\), respectively \(n_e\) the refractive index at \(\lambda_d=587.6\text{nm}\), \(V\) the Abbe number, and \(\Theta_{g,d}\) the secondary dispersion from wavelengths \(\lambda_g=435.8\text{nm}\) and \(\lambda_d\).

B. It exists a sufficiently dense area in the 3-dimensional space \((n_e, V, \Theta_{g,d})\) where any fictional triplet is close enough to a real triplet to ensure that passing from fictitious material to real one still allows the best optical performance at the end of the process.

Figure 1 shows the positions of every existing materials triplet in the 3-dimensional space \((n_e, V, \Theta_{g,d})\) for manufacturers CDGM, OHARA and SCHOTT, showing that assumptions A and B are here correct. These are densely distributed close to a polynomial surface that is considered as fulfilling the “sufficiently dense area” condition of assumption B. In the optimization design process, fictitious materials are characterized by two variables \(n_e\) and \(V\), and \(\Theta_{g,d}\) is derived from the above-mentioned interpolated surface equation. It is equivalent to letting the triplet of fictitious glass characteristics vary on the interpolated surface.
The indices for wavelengths of operation are then found from a 3-terms Cauchy model (1) derived from the materials parameters after solving a linear system with 3 unknowns $\alpha$, $\beta$ and $\gamma$:

$$n(\lambda) = \alpha + \frac{\beta}{\lambda} + \frac{\gamma}{\lambda^2}$$  \hspace{1cm} (1)

In addition, $n_0$ and $V$ are constrained physical values.

The optimization design process starts with a continuous optimization of fictitious models parameters $n_0$ and $V$, plus all the variables describing the geometry of the system. Once it has converged, the real materials are determined by finding the minimal Euclidean distance between the fictitious triplets $(n_0, V, \Theta_{g,d})$ and the real ones from chosen manufacturers catalogs. Then a second optimization starts with previously obtained geometry as the starting point to converge towards to the best optical system found. At this point, the tabulated 6-terms Sellmeier model from commercial data is used for best accuracy.

### 3 Results

To illustrate our method, we present results for an imaging system targeting the following characteristics:

- $N = 3.5$
- Focal length = 50 mm
- Field of view +/- 20°
- Wavelengths 656 nm, 588 nm, 486 nm
- No vignetting
- Distortion < 1%

Figure 2 (a) shows the optimized architecture with the optimized geometry and glasses. In Figure 2 (b), the modulation transfer function of this system is given up to 100 cy/mm which satisfies the required imaging quality. The most important result of our proposed method lies in the fact that the two optimized systems obtained at the end of each step have the same levels of optical performance whether designed with fictitious or real glasses. This shows that passing from fictitious to real glasses in this strategy preserves the optimality of the system.

### 4 Conclusion

We have proposed a 2-steps continuous optimization methodology for the selection of commercial glasses in an optical design loop, illustrated on a 6-lenses refractive optical system operating in the visible. In this example, the modulation transfer function up to 100 cy/mm clearly shows satisfying results according to specifications and reaches performance equivalent to those expected with fictitious glasses obtained by standard Code V design. The method can of course be generalized to any other spectral range and to more complex systems with more lens and/or aspheres. The main restriction is mostly given by one of our assumption making this method not applicable to spectral domain where much less materials are available. This methodology offers a great potential for efficient and enhanced design of the next generation of optical systems operating in the visible where the very large palette of existing glasses leads to a time consuming iterative selection made with the help of optical designer experts.

### References