

Framework for Automated Development and Modelling of Complex Optical Systems

Jona Wohletz* **, Marco Jordine*, Christian Becker*, Kevin Herrmann*, Tobias Biermann* **, Roland Lachmayer* **

**Institute for Product Development, Gottfried Wilhelm Leibniz University Hannover*

***Cluster of Excellence PhoenixD, Gottfried Wilhelm Leibniz University Hannover*

mailto:wohletz@ipeg.uni-hannover.de

Optical system development involves examining a high-dimensional parameter space. Understanding this solution space without excluding unconsidered designs presents an immense challenge. Therefore, a workflow is presented that includes all feasible solutions by a restriction of the solution space with constraints. Hereby only solutions which are in agreement with the requirements are considered. Inside the restricted solution space every design is simulated and compared.

1 Introduction

Optical systems are highly complex systems due to the interaction of various domains. Therefore, the development of such systems involves searching through a high-dimensional parameter space. Covering the entire search space comprehensively is a major challenge. In recent years, the steadily increasing implementation of algorithms and artificial intelligence (AI) in optical design mitigated that problem. Optical designer use a big variety of tools e.g. combinations of algorithms with AI for different applications [1][2]. Especially the field of photonic systems development has adopted design automation into their workflows [3]. For optical systems frameworks exist mostly for specific systems [4][5][6]. All of these works make an important contribution but they have in common that they only consider the optical domain. Depending on the application optical systems consist of several different domains. Including all of these domains in the simulation ensures a comprehensive characterization of the system but increases the amount of parameters for the simulation. To address this challenge, a constraint-based workflow is proposed [7]. Hereby, constraints enable a restriction of the solution space and establish a connection between parameters across domains. The workflow includes an exploration of the solution space, definition of constraints, restriction of the solution space and a simulation of every design from the restricted solution space.

2 Workflow

In this section, the proposed workflow is presented and the remaining challenges are discussed. The workflow follows the six phases of the MOKA methodology. In the identify phase, the engineering problem and its requirements are defined, and the corresponding parameter space is established. The justify phase motivates the acquisition and structuring of engineering knowledge to support the design

process. During the capture phase, knowledge is collected from scientific literature and technical references to establish an informal knowledge base describing the relevant physical and mathematical relationships. In the formalize phase, the informal knowledge base is converted into mathematical relationships and constraint equations that describe the dependencies between parameters and the specified requirements. Large language models can support knowledge acquisition [8], although verification, conflicting information, and potential bias remain important challenges. The package phase organizes the formalized knowledge into a reusable computational representation. Finally, in the activate phase, the resulting constraint satisfaction problem (CSP) is solved to determine feasible parameter sets, which are subsequently used as target values for simulation [9].

3 Example

In this section a short example is provided. The previously introduced workflow is explained based on the design of a focusing system for a Raman spectroscopy. The requirement is to achieve a defined intensity I_0 for the spot size of a Gaussian laser beam. The setup is shown in Fig. 1. Parameters that define the intensity are focal length f , wavelength λ , beam waist before the lens w_0 , beam waist at the spot size w_2 , Rayleigh range z_R , laser power P_0 , beam propagation ratio M^2 , beam diameter at the focusing lens D and the object distance d . Assuming a focused Gaussian beam, the spot size is defined as

$$w_2 = \sqrt{\frac{w_0^2}{\frac{z_R^2}{f^2} + \left(1 - \frac{d}{f}\right)^2}}.$$

The minimal achievable spot size is restricted by the diffraction limit to

$$w_{min} = \frac{4\lambda f M^2}{\pi D}.$$

The formular for the intensity for a Gaussian beam is defined as

$$I_0 = \frac{2P_0}{\pi w_0^2}.$$

Additional constraints from other domains could be absorption of the surrounding material, microfluidic constraints or molecular characteristics of the sample. In order to obtain the CSP the formulas are connected with mathematical operators and values are assigned to the parameters. For example, any feasible solution would have to satisfy the spot-size equation while also remaining above the diffraction limit. The CSP is solved with the python framework Raven CSP [10]. It uses a search algorithm supported by constraint propagation to identify solution parameter sets. Open questions remain regarding the level of abstraction: Which description of radiation is sufficient for which components? Additionally, rules specifying which domains are included and the depth at which they are considered must be established.

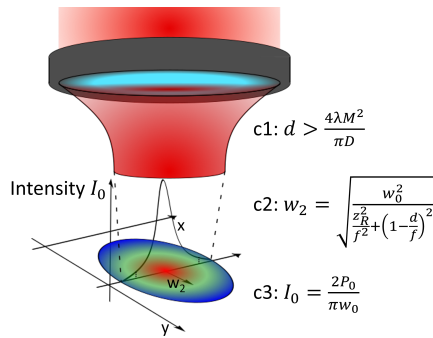


Fig. 1 Constraints for the intensity of the spot size of a Gaussian beam. Possible solutions in accordance with the requirements are determined by assigning values to the parameters.

4 Simulation

The aim of this section is to translate the obtained solution parameter sets into an optical design. To this end, a two-step simulation is employed. In a first step, paraxial initial designs are generated in order to compare different layouts. In a second step these initial designs are simulated more precisely, including a parameter optimization. For the initial design the previously determined solution values e.g. intensity I_0 from the CSP are adopted. These values define targets for the loss function of the simulation. For the first step of the simulation a wide variety of systems are generated and compared to select an initial set of candidates. Consequently, designs using the ray transfer matrix appears to be a suitable approach. It remains to be investigated whether a ray-optical or wave-optical description of light is more appropriate. This could also be adapted depending on the system or components. Furthermore the

derivation and definition of the loss function needs to be specified more precisely. The second part of the simulation requires a more detailed simulation for the selected designs. This includes a parameter optimization and a more comprehensive simulation of the system.

5 Conclusion

In this publication a workflow for the development of complex optical systems is proposed. It consists of an exploration of the parameter space combined with a subsequent restriction according to the requirements. Following, parameter sets in the solution space are determined and forwarded to the simulation. The simulation is divided into a first step to evaluate and determine initial designs and a second step with a final parameter optimization.

References

- [1] R. Maman, D. Ohana, J. Engelberg, and U. Levy, "Prompt-to-prescription: towards generative design of diffraction-limited refractive optics," (2026). 2602.13893, URL <https://arxiv.org/abs/2602.13893>.
- [2] A. P. Yow, D. Wong, Y. Zhang, C. Menke, R. Wolleschensky, and P. Török, "Artificial intelligence in optical lens design," *Artificial Intelligence Review* (2024).
- [3] B. MacLellan, P. Roztock, J. Belleville, L. Romero Cortés, K. Ruscitti, B. Fischer, J. Azaña, and R. Morandotti, "Inverse Design of Photonic Systems," *Laser & Photonics Reviews* (2024).
- [4] U. L. Wüllner, J. Wohletz, M. Jordine, M. Falkner, Z. Dai, T. Biermann, and R. Lachmayer, "Simulation-based development of an integrable optical deformation sensor using TIR prism rods," *International Society for Optics and Photonics (SPIE, 2026)*.
- [5] C. Fan, J. Zheng, X. Wan, X. Wei, and Y. Nie, "Differentiable Automated Design of Automotive Freeform AR-HUD Optical Systems," *Photonics* (2026).
- [6] J. Miao, T. Fu, M. Li, X. Zhang, and D. Wang, "Optical system initial structure generation method based on random assignment of optical power," *Optics and Lasers in Engineering* (2026).
- [7] A. Demircan, J. Wohletz, and T. Biermann et al., "Roadmap on 5D Photonics for nano and beyond," *Nano Futures* (2026).
- [8] S. Xie, T. Yang, Y. Xie, H. Ying, and Z. Wu, "LLM-Driven Multimodal Knowledge Graph Construction for Industrial Process With Prompt Optimization and Fuzzy RAG," *IEEE Transactions on Fuzzy Systems* (2026).
- [9] K. Herrmann, S. Plappert, P. C. Gembarski, and R. Lachmayer, "Process Chain-Oriented Design Evaluation of Multi-Material Components by Knowledge-Based Engineering," *Algorithms* (2023).
- [10] K. Herrmann, "CSP Modeling Interface 2," (2025). Accessed: 2026-07-31, URL <https://github.com/hermake/csp-modeling-interface-2>.