Potentials and Challenges of Generative Design for Additively Manufactured Freeform Optics

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The additive manufacturing of optical elements only partially exploits its design freedom as suitable design methods are not available and process characteristics complicate performance predictions. To account for this, a generative design method that generates and evaluates multiple solutions in parallel is proposed.

1 Introduction

Additive manufacturing (AM) creates new possibilities in many areas of technical product development. In the field of optics, the ability to produce geometries with greater design freedom compared to conventional manufacturing is of particular interest (Fig.1 a) [1, 2]. However, AM-generated optics have not been widely used in practice. A major reason is the anisotropic behavior and surface deviations resulting from layer-by-layer geometry generation (Fig. 1 b). These lead to optical characteristics, difficult to predict and account for in conventional optics design processes. [3, 4]

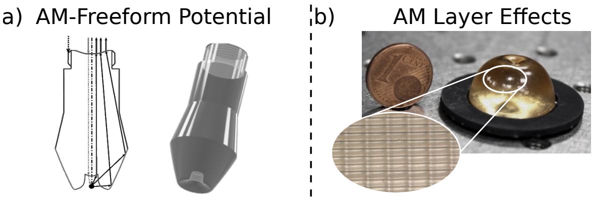

Fig. 1 *a) Design Freedom in Optics-AM as demonstrated in [4]; b) Surface of AM-Freeform Lens with visible layers*

Another aspect is that optical design typically focuses on lens geometries with low geometric complexity to simplify manufacturing. This limitation prevents optical designers from fully exploring the solution space available through AM. One approach to finding solutions in complex solution spaces can be generative design [5, 6]. This paper places generative design in the context of design automation, describes necessary implementation steps and outlines potentials and challenges along the way.

2 Implementation Levels to Automated Design

The automation of design processes can be divided into parametric design (PD), algorithms-aided design (AAD) and generative design (GD) in the order of an ascending degree of automation (Fig. 2). In PD, geometry defines through parameters, rules and mathematical formulas [5]. An example of this is the automated adjustment of a dimension when another dimension is changed. In AAD, automation is extended so that more complex solution-finding systems, for example iterative optimizations, are used [7]. Here, the geometry is no longer directly influenced by the designer but by the algorithm. GD automates the design process in which the designer specifies the boundary conditions of the object to be generated, after which the design process automatically generates a number of possible solutions [5, 6]. These are first evaluated automatically and subsequently selected and optimized by the designer.

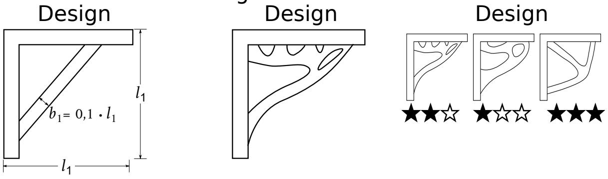

Fig. 2 *Comparison of Parametric, Algorithms-Aided and Generative Design*

In contrast to mechanical and structural components, which are mostly redirecting forces between predefined points, the geometric shape of an optical element is directly related to the function, i.e. the reshaping of a light distribution. Therefore, in the approach taken here, current optical design is already primarily in the realm of AAD.

3 Components of an Optics GD Environment

To build a GD environment, Krish defines three core elements: A way to represent the problem as a schema or formula relationship (parametrization), a way to generate variations and a way to select suitable outcomes [6].

3.1 Specifying the Optical Design Problem

To specify optical design problems, two main approaches exist: multiparameter optimization and di-

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rect modeling [8]. Multiparameter optimization, common in software like Zemax OpticStudio, creates an initial system and parameterizes it. Boundary conditions including the target light distribution are defined in a merit function and its parameters are varied until it is sufficiently satisfied. Advantages are a widespread use and the easy search for solution variations. Disadvantages are a high computational cost and a need to constrain the solution space. [8]

In contrast, direct modeling models the surfaces of an optical element as a mathematical relationship between the source and target light distributions. While the results are difficult to manufacture using conventional methods, AM reduces such limitations. The individual methods differ in applicability, whether they redirect from a point light source or map an extended light source. Advantages are a low optimization effort and fast adaptability. A Disadvantage is the difficulty in generating alternative solutions since each method usually allows only one solution. [8]

3.2 Automated Generation of Solution Variations

To ensure the generation of alternative solutions despite the complexity of multi-parameter optimization and the mathematical uniqueness of direct methods, it may be useful to combine direct modeling with multi-parameter optimization. In this case, an initial geometry would be generated with the help of direct modeling, which subsequently serves as the starting point for multiparameter optimization. Since multiparameter optimization cannot improve the result if the initial conditions are the same, this transition step can be used both to remove initially required assumptions such as that of point light sources and to incorporate surface and volume properties such as staircase effects and anisotropies.

3.3 Selection of Suitable Design Variants

When selecting solutions, two aspects are crucial: the sufficient suitability of the solution and its robustness against manufacturing errors. Direct methods and sufficiently fulfilled merit-functions in multiparameter optimization ensure the basic suitability. The challenge lies in modelling manufacturing errors, which can only be done stochastically due to the limited repeatability in relevant AM-processes.

The detailed modeling of deviations inside the individual layers and their interaction is mathematically complex. Therefore, it makes sense to preselect multiple suitable solutions in a low complexity simulation. While incrementally increasing simulation accuracy more solutions can be elimnated to reduce the overall computational effort.

4 Conclusion

A GD environment offers high potential to aid in modeling complex freeform optics and to make better use of the available solution space. However, challenging is the selection of a suitable modeling approach, the efficient generation and evaluation of suitable variants and the approach generalization.

One possibility may be to combine direct modeling with multiparameter optimization, where direct modeling is used to generate an initial geometry that serves as the starting point for multiparameter optimization. During transition, further assumptions regarding the design can be incorporated, such as extended light sources and anisotropic behaivour.

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