

Robust design for 3D-printed optomechanical systems

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This paper proposes a systematic integration of robust design principles into the development of 3D-printed optomechanical systems, aiming to address key challenges such as print quality, process stability, and the high sensitivity of optical systems, and to enhance the reliability and performance of printed optomechanical components.

1 Introduction

In recent years, extensive research has been conducted on the development of 3D-printed optical components, mounts, and enclosures, demonstrating their potential for optical applications [1] [2]. However, current 3D-printed macroscopic optomechanical systems still face challenges such as insufficient stability and limited precision, which hinder their widespread adoption in high precision optical applications. To improve the performance and reliability of 3D-printed optomechanical systems, this paper reviews recent advancements in the field and analyzes its key advantages and challenges. Furthermore, a robust design-based optimization strategy is proposed to enhance the stability, precision, and overall performance of 3D-printed optomechanical systems, providing a reference for future high precision optomechanical designs.

2 Advances and Development Trends of 3D-Printed Optomechanical Systems

In the past decade, 3D-printed optomechanical systems have primarily been utilized in laboratory settings, offering a flexible and cost effective alternative to expensive optomechanical components, such as 3D-printed optical supports, mounts and optical adjustment platforms. As the application of 3D printing continues to expand, it has started to challenge entire optomechanical systems. Over time, 3D printed structures have been optimized to better integrate with the technology. Examples of such systems include 3D-printed microscopes and compact spectrometer systems [3]. Innovative developments in 3D-printed optomechanical systems are emerging, with the advantages of 3D printing becoming evident in design innovation. Additionally, structural designs that incorporate both rigidity and spring-like flexibility can now be realized in a single component, allowing for passive lens mounting. Furthermore, 3D printing enables the integration of various optomechanical components, reducing the number of parts

required in the system assembly.

3 Advantages and Challenges of 3D-Printed Optomechanical Systems

3D-printed optomechanical systems offer several advantages, such as flexibility, cost-effectiveness, and design innovation. Rapid prototyping allows for the validation of complex optical systems, reducing development time and enabling customized solutions. Additionally, 3D printing facilitates the creation of intricate geometries that are difficult to achieve with traditional manufacturing, leading to lightweight and integrated systems. Furthermore, by combining multiple components into a single printed part, the complexity of assembly is reduced, improving system reliability. However, the precision and stability of 3D printing are insufficient for high precision optomechanical systems, which can lead to performance degradation or failure to meet specifications. This is mainly caused by dimensional deviations due to volume shrinkage and structural deformations from uneven stress distribution. Achieving the necessary precision often requires extensive trial and error in the design and assembly process. Additionally, developing innovative designs that fully exploit the benefits of 3D printing while ensuring optimal performance remains a significant challenge.

4 Methodology for 3D-printed Robust Optomechanical Systems

The goal of robust design is to ensure that system performance remains insensitive to variations in manufacturing and assembly processes, maintaining stable performance under different environmental and operational conditions. For 3D-printed optomechanical systems, robustness is primarily influenced by the instability of the 3D printing process, limited fabrication precision, and the stringent tolerance requirements of optical systems. For example, the performance of an optomechanical system can

significantly degrade due to variations in the position and angle of optical components. Therefore, optimizing tolerances during the design phase is crucial. This paper proposes a robust design method based on tolerance control, using tolerance analysis as an iterative optimization criterion to refine optical design, 3D printing parameters, and structural design during the virtual prototype stage. The specific workflow is shown in Figure 1. The design of the optomechanical system begins with system requirements, followed by the design of the initial optical system based on the optical path and the direct generation of the mechanical structure design. During the design phase, a virtual prototype is developed using numerical modeling of 3D printing processes combined with finite element analysis (FEA) to predict the manufacturing tolerances of mechanical components. Then, tolerance analysis is conducted by integrating both optical and mechanical tolerance requirements to evaluate the system performance. If the system performance fails to meet the criteria, iterative optimization is carried out across optics, mechanics, 3D printing parameters, and tolerance control until the system satisfies the requirements. Finally, the optimized design will be validated through actual printing and experimental stages to test performance stability and reliability.

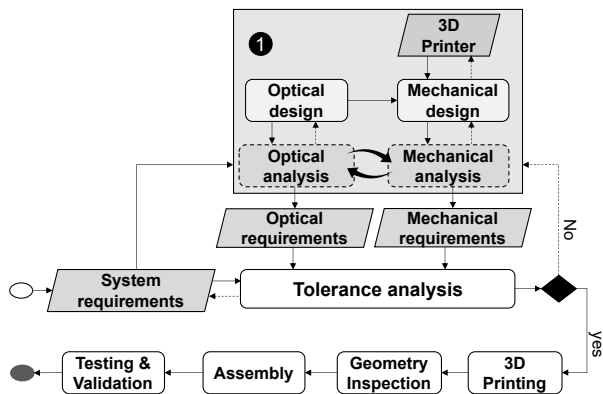


Fig. 1 Workflow of 3D-printed optomechanical systems: a robust approach through tolerance control

During the iterative optimization phase (part 1 in Figure 1), four different perspectives are considered, as illustrated in Figure 2. Due to the nature of 3D printing, both printing parameters and geometric structures have a significant impact on the final outcome. The first perspective involves optimizing 3D printing parameters based on the virtual prototype. The second focuses on structural design optimization using FEM predictive models, aiming to improve rigidity or optimize stress distribution. The third concerns optical design, including constructing and optimizing systems with lower sensitivity to mechanical tolerance and performing tolerance sensitivity reduction. The fourth perspective is tolerance design, which involves reallocating tolerance requirements based on component sensitivity and the

anisotropic characteristics of 3D printing accuracy.

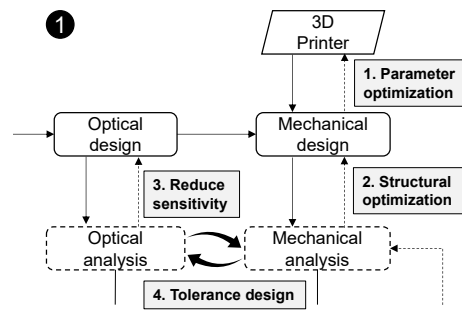


Fig. 2 Key optimization perspectives for enhancing the robustness of 3D-Printed optomechanical systems

5 Conclusion and Outlook

This paper proposes a robust design process for 3D-printed optomechanical systems, aiming to address challenges related to structural stability and optical precision. The proposed framework integrates optical path design, optomechanical structural modeling, and 3D printing parameter optimization in the design phase. Tolerance analysis serves as the foundation for an iterative optimization mechanism to improve overall system robustness.

This methodology provides a new approach to the design of 3D-printed optomechanical systems, enhancing their potential applicability in high precision optical applications. Future work can further refine this process by incorporating material selection, optimization of printing techniques and postprocessing methods, and exploring data-driven optimization strategies to enhance the reliability and precision of 3D-printed optomechanical systems.

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