From an Analytical Formulation to a Digital Image Processing Strategy for Contour Hologram Synthesis

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Abstract

A novel strategy is proposed to synthesize light beams tracing arbitrary closed contours using a digital image processing approach. The method operates directly from a binary mask, replacing complex analytical parameterization and continuous integration with discrete, grid-based operations. This transition enables high-fidelity synthesis for a wide range of shapes. Numerical simulations validate the accuracy and efficiency of this image-based process for generating complex structured light beams.

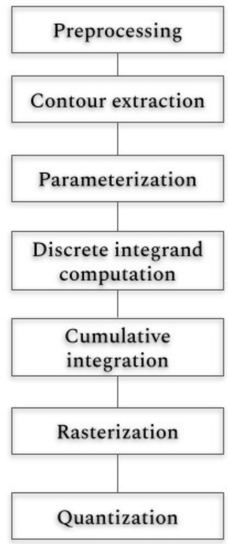
Introduction

Structured light beams, particularly those carrying Orbital Angular Momentum (OAM), are essential tools in advanced optics, including super-resolution microscopy and optical trapping. Spatial Light Modulators (SLMs) are key to generating these beams by displaying calculated phase holograms.

The traditional synthesis of holograms for beams with arbitrary, user-defined intensity contours relies on complex analytical formulations or slow iterative methods, which are computationally demanding and lack flexibility for real-time applications.

We present a non-iterative, single-step methodology that entirely bypasses these limitations. Our approach transforms the problem from a continuous mathematical inverse problem into a discrete digital image processing task, enabling the rapid and accurate synthesis of light beams whose intensity profiles precisely match any input binary mask.

Materials and methods



A binary mask representing the target contour is imported.

Edge detection is implemented. Pixels are ordered.

Contour pixels are implicitly parameterized by ordered index.

Continuous variables (***x, y***) and differentials (***dx, dy***) are replaced by (***Δx, Δy***) operating directly on the SLM grid.

A discrete running sum is performed cyclically along the ordered contour pixels, generating $\Phi_{contour}$

Hologram Generation. The contour-indexed phase is rasterized onto the SLM grid and quantized to a bit-depth.

Fig.1. Block diagram of this proposal.

Results

The proposed method achieves high performance in both fidelity and computational speed for a diverse set of contours.

Numerical simulations demonstrate that the generated light beams accurately trace the input binary masks in the Fraunhofer plane.

Cross-correlation coefficient between the target mask and the simulated intensity typically exceeds 0.96

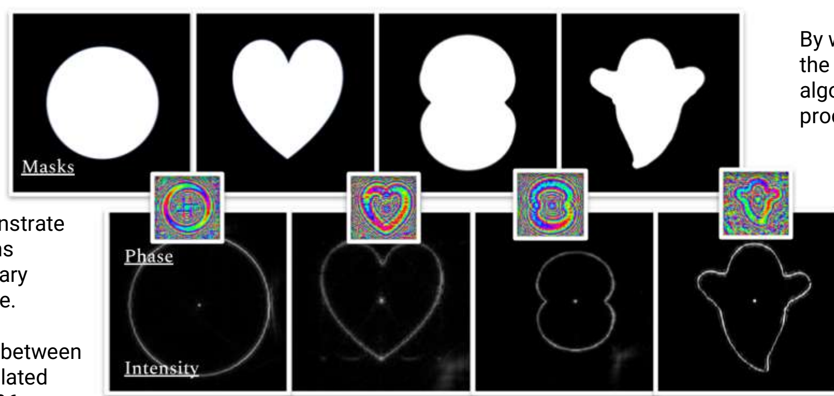


Fig.2. Example of Intensity and phase distributions (represented in a color scale from 0 to 2 π) simulated for four different masks.

By working exclusively in the discrete domain, the algorithm minimizes processing time.

Hologram generation for a 256 x 256 grid is achieved in approximately on less than 1 s on standard desktop hardware.

Conclusions

Numerical simulations validate the high fidelity of the synthesized light beams, which accurately trace the input binary masks (normalized cross-correlation is at least 0.96). This proposal significantly reduces computational time, achieving high-performance results without relying on time-intensive analytical integrations or iterative routines. This transition enhances both computational efficiency and design flexibility for complex structured light beams.

As future work we look forward to:

Implement further validation using a larger dataset of user-defined, freehand drawn contours to test the robustness of the contour detection algorithm.

Extending the methodology to 3D beam shaping applications, allowing for light propagation along arbitrary curves in space.

References

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