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Experimental Evaluation of a Zernike-Mode-Based Hill-Climbing Algorithm for Adaptive Optics

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Abstract

The use of adaptive optics in ultrafast laser manufacturing has demonstrated significant benefits in mitigating non-ideal effects related to excessive energy concentration, commonly associated with modern ultrafast laser systems. Among the available solutions, deformable mirrors represent a suitable compromise in terms of efficiency, flexibility and ease of integration, and are typically controlled through Zernike polynomials. In this work, an analytical model based on Physical Optics Propagation is combined with a Hill Climbing optimization algorithm to determine the Zernike polynomial combinations required to generate specific target spot shapes. The approach is experimentally implemented and validated, allowing direct comparison between model predictions and measured results. The analysis highlights both the capability of the model in identifying the most relevant Zernike modes and its limitations in accurately predicting coefficient t amplitudes under real experimental conditions.

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Keywords: adaptive optics; Hill Climbing algorithm; Zernike modes; Deformable Mirror;

1. Introduction

Ultrafast laser processing enables high-precision micromachining of brittle and hard materials thanks to the extreme peak intensities of ultrashort pulses, which activate both linear and non-linear interaction mechanisms [1–3]. Applications include precision glass processing and surface functionalization through Laser-Induced Periodic Surface Structures (LIPSSs) [4,5]. However it is also well known that one of the most important limitations of ultrafast laser processing is that excessive pulse energy and high repetition rates may reduce ablation efficiency, induce uncontrolled cracking, and compromise process stability due to limited thermal relaxation [6].

Dynamic beam shaping represents a promising strategy to directly tailor the fluence distribution at the target [7–9]. Several technologies have been proposed, including coherent beam combining, digital micromirror devices and spatial light modulators [10–12]. Among these, Deformable Mirrors (DMs) provide a robust and efficient solution for high-power systems. A DM modifies the incoming wavefront by actuating a reflective membrane through piezoelectric elements, and the resulting deformation is commonly described using Zernike polynomials [13,14].

Although Zernike-based modal control is widely adopted, the relationship between coefficient values and focal intensity distribution is not analytically invertible and is often treated as a black-box problem [15,16]. This work investigates the feasibility of combining Physical Optics Propagation (POP) with a Hill Climbing (HC) optimization

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algorithm to predict the most relevant Zernike modes required to generate predefined target intensity shapes. The method is experimentally validated and compared with simulation results.

2. Simulative analysis

Adaptive optics modelling requires a wave-optics framework to account for diffraction and interference effects beyond geometrical optics. Beam propagation is modelled using scalar diffraction theory under Fresnel and Fraunhofer approximations derived from the Rayleigh–Sommerfeld formulation. Free-space propagation is implemented numerically through a two-dimensional Fast Fourier Transform (FFT), allowing efficient computation of the complex electric field evolution. Several commercial and open-source software packages have been developed for Physical Optics Propagation simulations, including Zemax OpticStudio, QUADOA, Commod Pro, POPPY, PAOS, PROPER and LightPipes [17–26]. Optical elements such as lenses are modelled as multiplicative phase masks applied to the propagating field:

$$t_{lens} = \exp[jk\Delta 0] \cdot \exp[jk(n-1)\Delta(x,y)] \qquad (1)$$

where k = 2π λ is the wavenumber, n the refractive index of the lens material, and Δ(x, y) the shape of the lens, expressed as a thickness function of the component.

Wavefront aberrations are introduced as additional phase terms applied to the pupil function:

$$F_{out}(x,y) = e^{\phi_n^m(x,y)} F_{in}(x,y) \qquad (2)$$

where Fin is the input electric field, Fout the field after the phase mask, and ϕmn the added phase.

The phase term ϕmn is decomposed over Zernike polynomials, which form an orthogonal basis over the unit circle. Each Zernike coefficient is directly related to the RMS wavefront error of the corresponding aberration mode [14,27]. This orthogonality ensures independent modal control and makes Zernike representation particularly suitable for describing deformable mirror actuation.

Since no direct inverse mapping between focal intensity distribution and Zernike coefficients can be analytically derived, the problem can be formulated as local optimization problem. Among the available approaches, the Hill Climbing (HC) algorithm was selected due to its simplicity and effectiveness in high-dimensional search spaces where the evaluation of each candidate solution is computationally expensive.

The Hill Climbing (HC) algorithm iteratively explores neighboring solutions and retains parameter combinations that improve the objective function [28]. This approach provides a favorable trade-off between solution quality and computational cost, enabling rapid identification of suitable Zernike mode combinations within a limited computational budget. However, as a local optimization method, it may converge to local optima depending on the structure of the search space.

The search space is discretized with an adaptive step size Δ, progressively reduced by a convergence factor α to enhance stability. Termination criteria include maximum iteration number and negligible improvement of the similarity metric between simulated and target intensity distributions. The overall optimization workflow combining Physical Optics Propagation and the Hill Climbing algorithm is schematically illustrated in Figure 1.

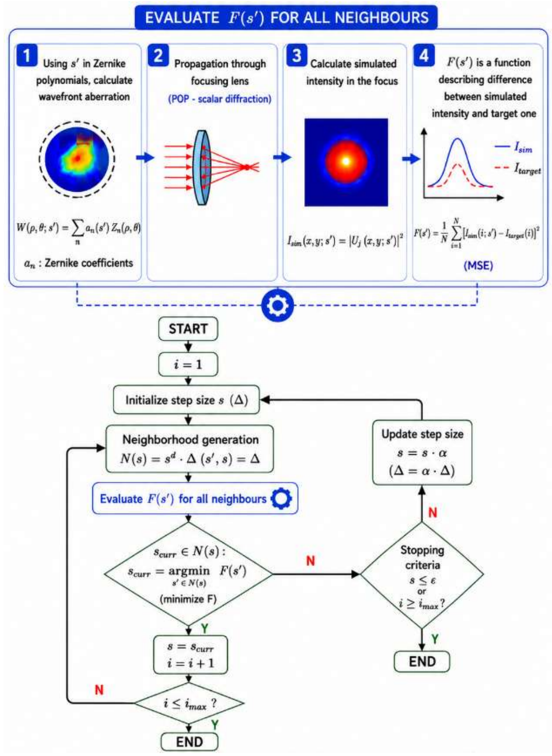


Figure 1: Schematic representation of the proposed optimization workflow combining Physical Optics Propagation (POP) and the Hill Climbing (HC) algorithm.

The algorithm was tested on three industrially relevant target shapes [31–33]: Ellipsoidal distribution, Top-hat profile Donut profile. In the absence of external aberrations, the algorithm successfully identified the combination of Zernike coefficients required to approximate the desired shapes and the corresponding optimization results for the ellipsoidal, donut, and top-hat target distributions are reported in Figures 2–4, respectively.

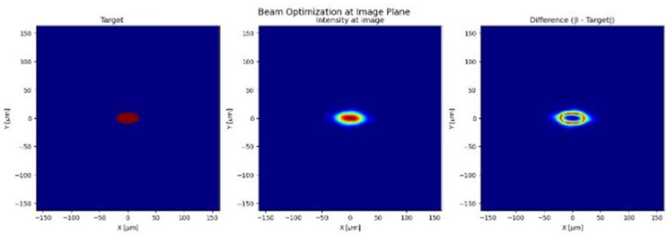


Figure 2: Result of the optimization algorithm for an ellipsoidal shape

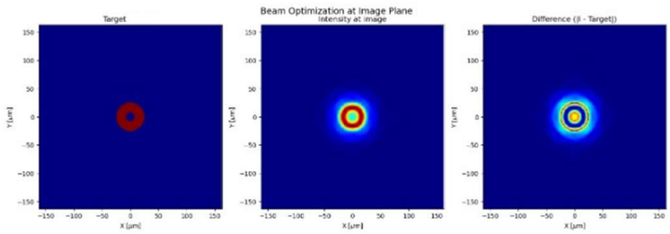


Figure 3: Result of the optimization algorithm for a donut shape.

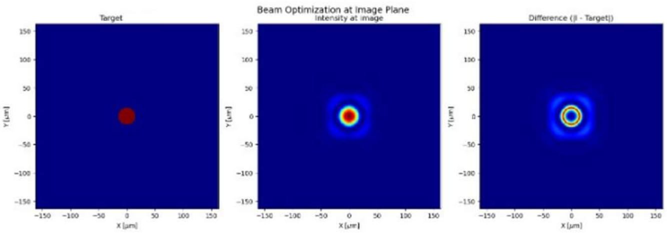


Figure 4: Result of the optimization algorithm for a top-hat shape.

3. Simulation and experimental results

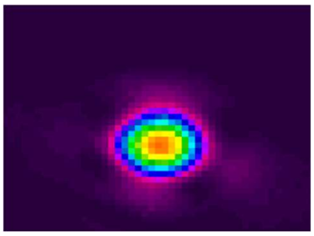
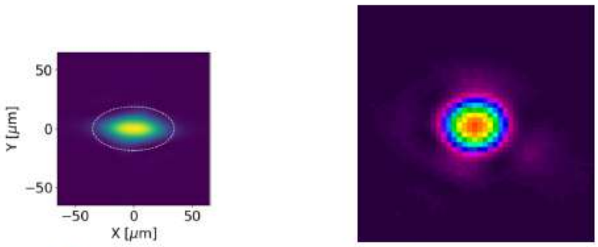


Figure 5: Spot at focus in the experimental setup with no DM



(a) Python optimization.

(b) Experimental results.

Figure 6: Simulation and experimental validation of an ellipsoidal shape.

The experimental validation was performed using a continuous-wave He–Ne laser source operating at 632.8 nm. Such source was selected to guarantee high spatial coherence, stable output power, and near-ideal Gaussian beam quality. Moreover, the use of a low-noise visible source simplified both alignment procedures and wavefront characterization. The beam was coupled into a 630HP single-mode fiber and collimated with an achromatic lens, collimated through an achromatic doublet lens to minimize chromatic and spherical aberrations while generating a uniform beam diameter compatible with the active aperture of the deformable mirror (specifically, beam diameter 12 mm). The collimated beam was reflected by a 32-actuator piezoelectric deformable mirror and then focused by a plano-convex lens with focal length 150 mm.

A Shack–Hartmann wavefront sensor was used for wavefront monitoring. The measured wavefront information was also used to evaluate the presence of residual aberrations in the baseline optical configuration. The focal intensity distributions were acquired using a BeamGage CMOS camera. The camera allowed high-resolution characterization of the beam profile and enabled quantitative extraction of parameters such as beam diameter, ellipticity, and energy distribution uniformity. In particular, D4σ beam diameters were used as quantitative descriptors for comparing simulated and experimental focal shapes. All optical components were mounted on 5-axis micro-positioning stages to minimize misalignment and additional aberrations. Despite careful alignment, residual spherical aberration and slight astigmatism were observed in the baseline configuration, mainly due to mechanical tolerances and imperfections of the optical components.

A simplified aberration-free version of the optical system was first simulated using the POP model. Under ideal alignment and without external perturbation, the focused ideal beam reached a diameter of approximately 21.9 µm at the image plane. Figure 5 shows the focal spot acquired experimentally in the absence of deformable mirror modulation. The spot acquired experimentally was in contrast with the ideal numerical prediction since the unmodulated focal spot exhibited slight astigmatism, with measured values: D4σX = 41.39 µm and D4σY = 38.68 µm.

The first target distribution was an ellipsoidal profile; for this shape, the HC algorithm predicted defocus (Z4) and astigmatism (Z6) as the dominant modes for generating an ellipsoidal intensity distribution (20 µm × 10 µm). Experimentally, the same modes produced the expected elongation, although higher coefficient amplitudes were required to compensate for residual system aberrations. The comparison between simulated and experimentally generated ellipsoidal profiles is shown in Figure 7.

Targeting a 15 µm radius top-hat distribution, higher-order spherical and quadrifoil terms were identified as significant contributors. Experimental implementation through the DM resulted in a flattened intensity profile, with measured values: D4σX=45.65µm and D4σY = 41.73 µm. Although the overall profile shape was consistent with the simulated prediction, residual oscillations and non-uniformities were visible at the beam edges. These effects are likely associated with the finite spatial resolution of the deformable mirror, actuator cross-coupling, and the limited ability of the system to perfectly reproduce high-spatial-frequency phase variations. Furthermore, the Fraunhofer approximation adopted in the numerical model may partially neglect secondary propagation effects occurring in the real optical configuration. The comparison between simulated and experimental top-hat intensity distributions is presented in Figure 7.

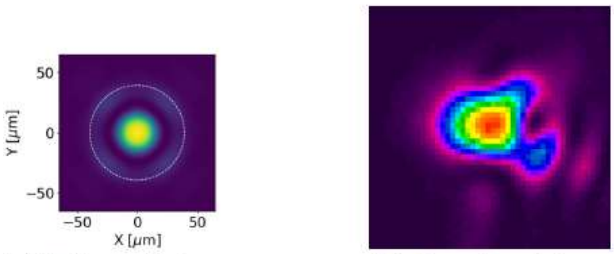


Figure 7: Simulation and experimental validation of a top-hat shape.

Lastly, for a triangular shape, it was primarily influenced by trefoil modes Z9 and Z10. Experimental activation of the corresponding coefficients successfully reproduced a strongly asymmetric focal distribution consistent with the numerical trend. While the exact geometric sharpness predicted by simulation was not fully achieved, the resulting intensity profile clearly demonstrated the capability of the adaptive optics system to generate complex nonaxisymmetric beam shapes. This result is particularly relevant for advanced laser material processing applications where directional energy deposition and asymmetric melt dynamics may be beneficial.

Overall, the comparison between simulations and experiments demonstrates that the proposed HC-POP framework is capable of reliably identifying the dominant Zernike modes associated with specific target beam shapes. Although the exact coefficient amplitudes differ between ideal and experimental conditions, the method significantly reduces the dimensionality of the optimization problem and provides a physically meaningful initialization for experimental tuning procedures.

The remaining discrepancies between simulation and measurements can be attributed to several factors, including residual optical aberrations, finite actuator stroke, hysteresis effects of the deformable mirror, beam alignment tolerances, and the simplifying assumptions inherent to scalar diffraction modeling. In particular, the Fraunhofer approximation neglects certain near-field propagation effects and polarization-related phenomena that may become relevant in real optical systems.

Nevertheless, the results confirm that the combined HC-POP strategy represents an effective and computationally efficient tool for adaptive optics beam shaping. The approach enables rapid identification of the most relevant aberration components while maintaining sufficient flexibility for experimental implementation in practical laser manufacturing environments.

4. Conclusion

This work investigated the feasibility of combining Physical Optics Propagation with a Hill Climbing algorithm for Zernike-based beam shaping. The proposed approach successfully identified the dominant aberration modes required to generate different target intensity distributions, showing good qualitative agreement between simulations and experimental results. Despite the need for larger coefficient amplitudes in real conditions, the framework proved effective in reducing experimental tuning effort for adaptive optics applications in laser material processing.

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