Multispectral Extended Depth-of-Field Imaging via Stochastic Wavefront Optimization

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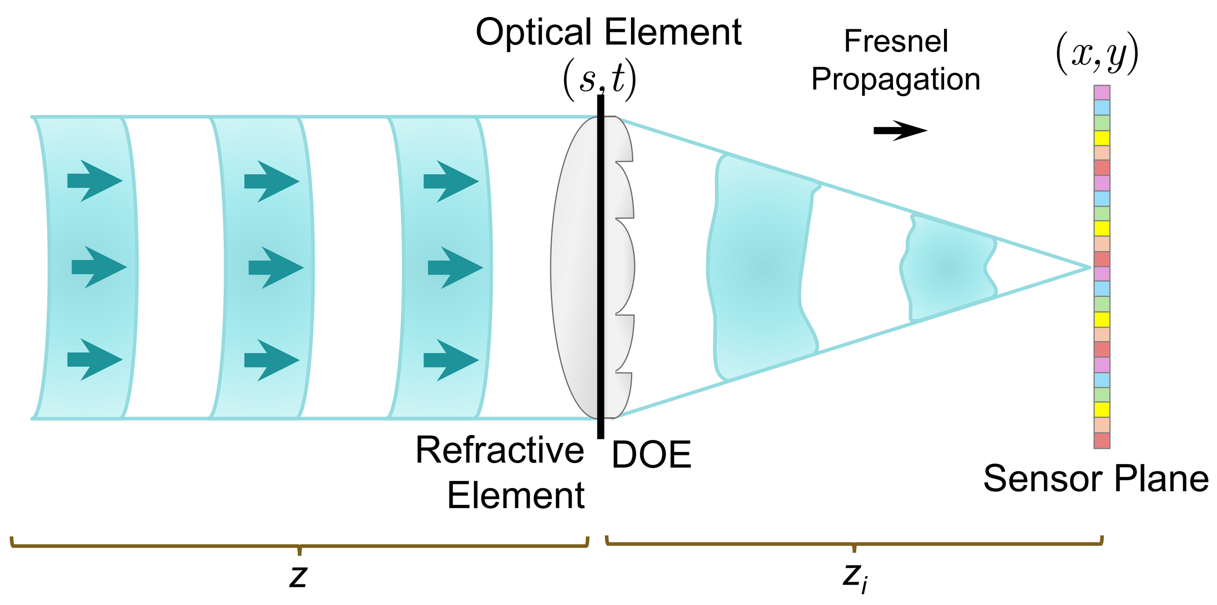
INTRODUCTION

We propose a wavefront coding approach using a diffractive optical element (DOE) optimized via stochastic methods to achieve **multispectral (MS) extended depth-of-field (EDoF)**. Our simulation-driven design improves both spectral fidelity and depth invariance, and it is compared against three state-of-the-art designs: the cubic phase mask [1], End-to-End (E2E) design [2], and Hardware-in-the-Loop (HIL) design [3].

SENSING MODEL

PROPAGATION SCHEME



The acquisition of our system captures a blur measurement given by

$$\overline{\mathbf{X}}_{\lambda,z} = \mathbf{PSF}_{\lambda,z} * \mathbf{X}_{\lambda,z} + \mathbf{\Omega}_{\lambda,z},$$

where $\mathbf{X}_{\lambda,z} \in \mathbb{R}^{\mathrm{M\times N\times L\times Z}}$ represents the spectral-depth datacube, with M and N as spatial dimensions, L as the spectral dimension, and Z as depth for a single spectral band at a depth z. The operator $*(\cdot)$ denotes convolution, corresponds to the 4D point spread function (PSF), and $\mathbf{PSF}_{\lambda,z} = |\mathcal{F}\{\mathbf{Q}_{\lambda,z}(s,t)\}|^2$ is the PSF for each spectral-depth. Here, $\mathcal{F}(\cdot)$ denotes the Fourier transform, $\mathbf{Q}_{\lambda,z}(s,t)$ represents the generalized pupil function, and $\mathbf{\Omega}_{\lambda,z}$ represents the additive noise. The DOE phase mask is defined by

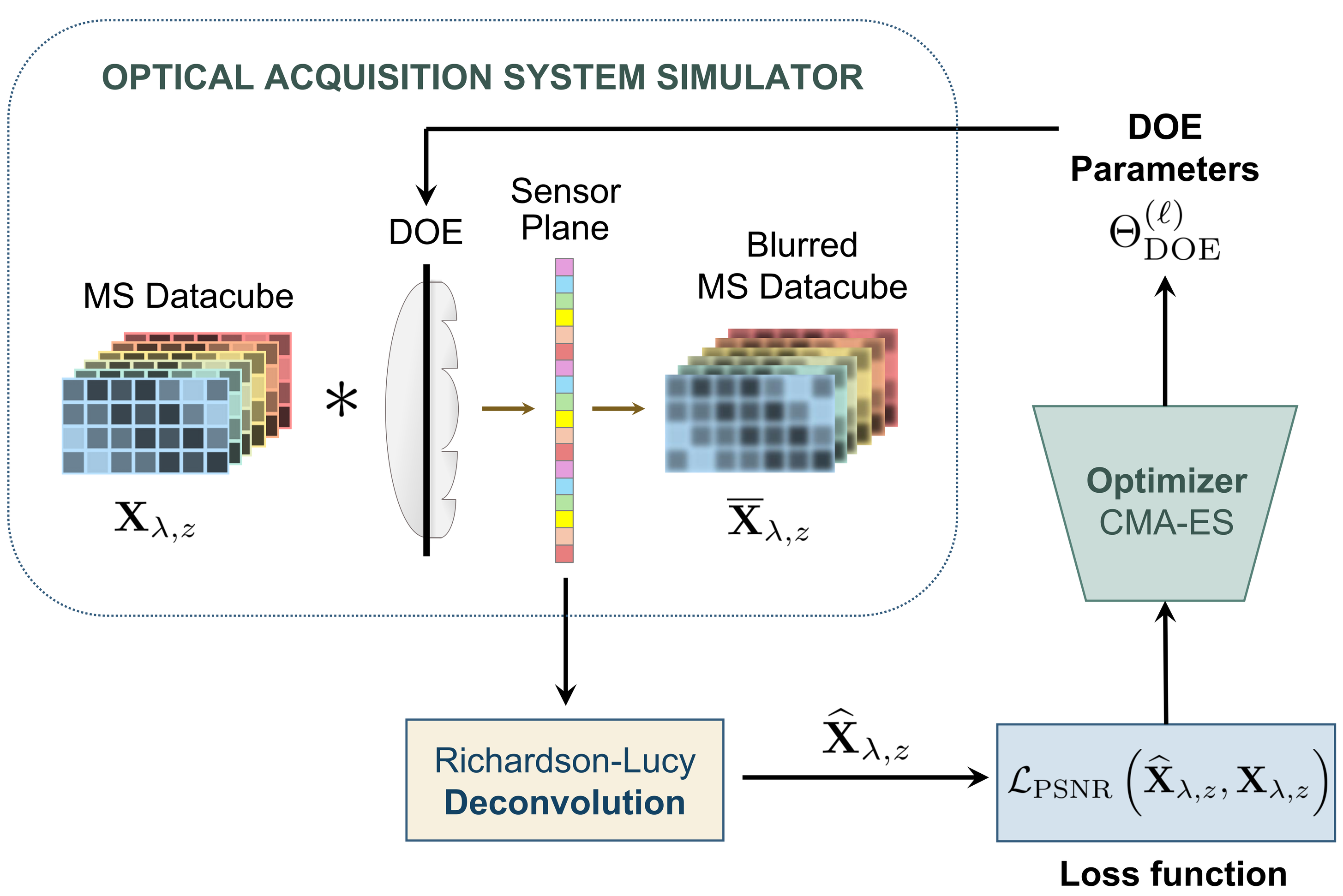
$$h(s,t) = \alpha(s^3+t^3) + \sum_{p=1}^{14} \rho_p Z_p(s,t),$$

where $Z_p(s,t)$ are the p^{th} Zernike Polynomial with coefficient ρ_p to be estimated, and α is the cubic phase coefficient.

METHODS

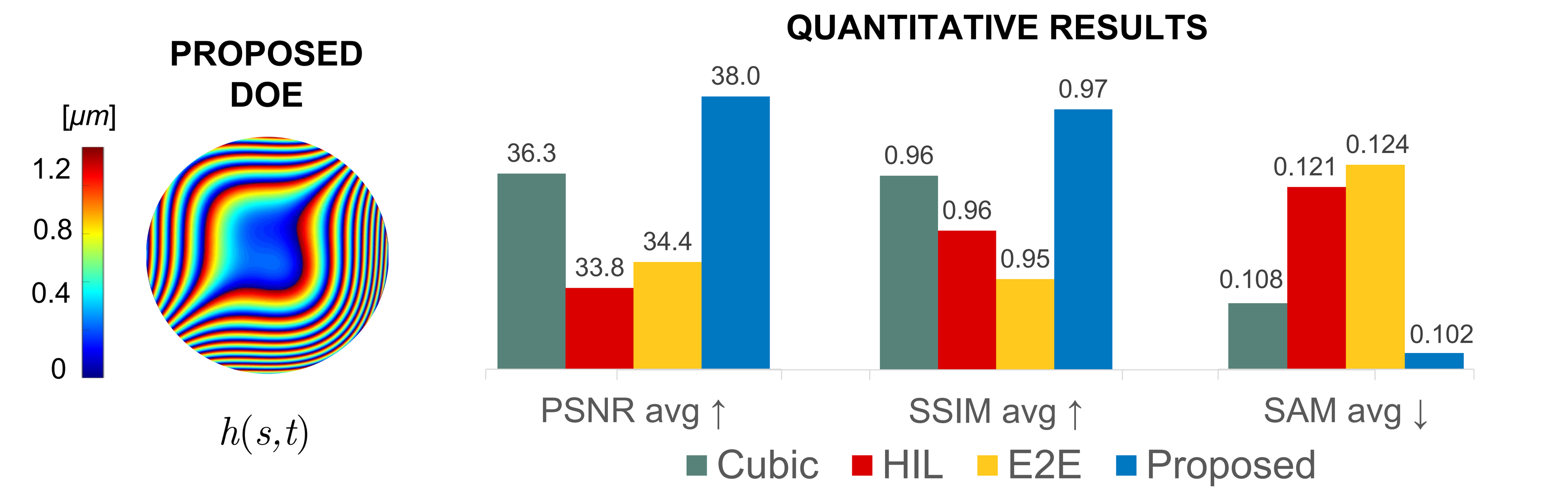
We simulate a multispectral imaging system where a DOE modulates the wavefront before image formation. The DOE phase is optimized using the CMA-ES algorithm to maximize reconstruction quality based on PSNR [2]. The pipeline includes Fresnel propagation, Richardson-Lucy deconvolution for evaluation, PSNR loss and CMA-ES optimizer. The set of parameters to be optimized is given by

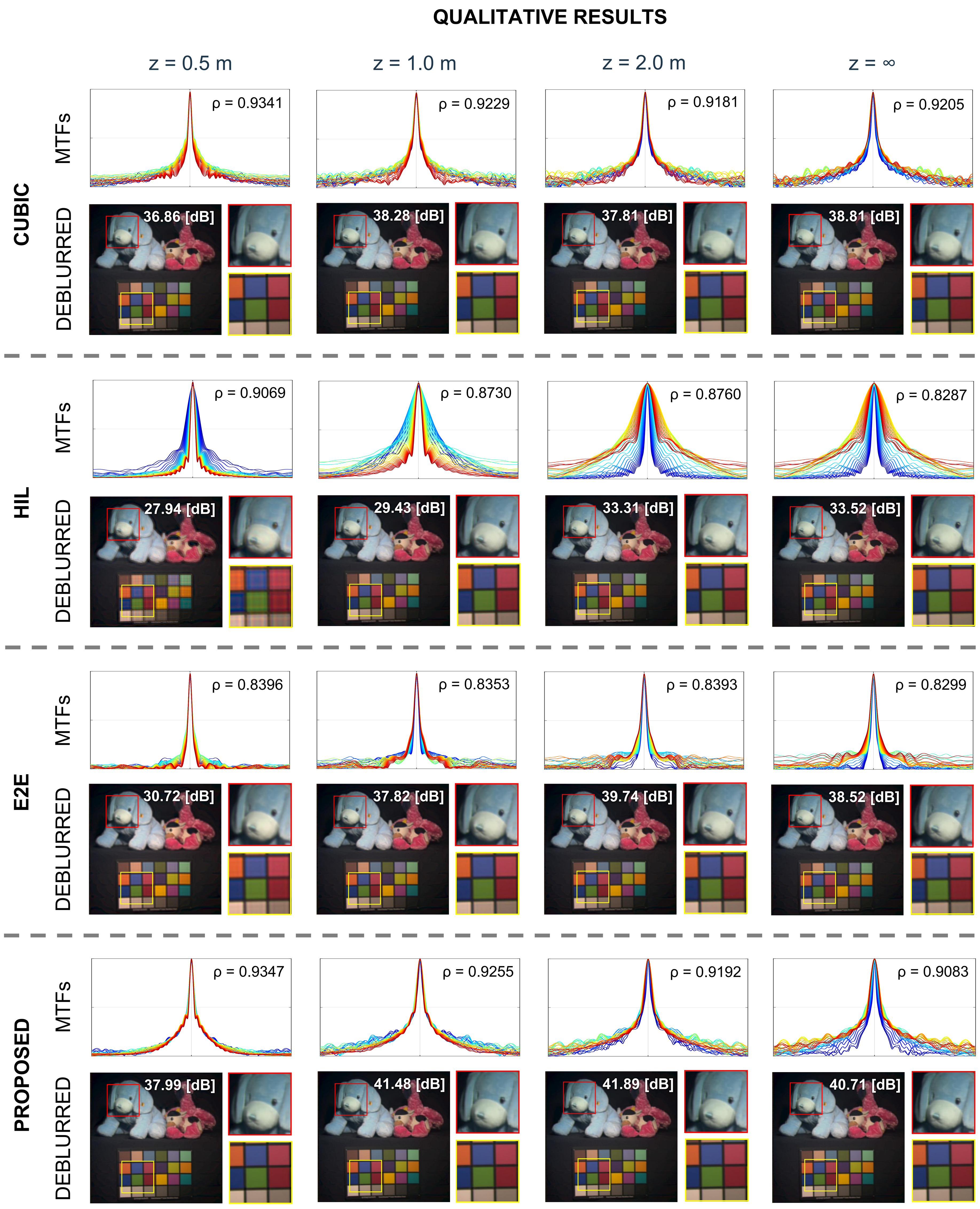
$$\Theta_{DOE} = (\alpha, \rho_1, \ldots, \rho_P).$$



RESULTS

Spatial and spectral quantitative and qualitative comparison between three state-of-the-art DOEs and the proposed DOE design. Metrics include averaged PSNR, SSIM, and SAM (Cave dataset), as well as Pearson's correlation coefficient (ρ) for similarity between modulation transfer functions (MTFs).





CONCLUSIONS

The proposed stochastic optimization framework enables the design of a DOE that enhances both spatial and spectral fidelity while extending depth-of-field. It **outperforms state-of-the-art methods across multiple metrics and imaging conditions**. This approach is simulation-driven and compatible with various multispectral sensor architectures.

Paper IEEE OJSP

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FUNDING: ANID FONDECYT 1221883, FONDECYT POSTDOCTORADO 3230489, ANILLOS ATE220022.