Multispectral Filter Array by Optimal Sphere Packing

N. Diaz[1*], A. Alvarado[1], F. Guzman[1], P. Meza[2] and E. Vera[1]
[1]School of Electrical Engineering, Pontificia Universidad Católica de Valparaíso
[2]Department of Electrical Engineering, Universidad de la Frontera
* nelson.diaz@pucv.cl

Introduction

This paper propose a Multispectral Filter Array (MSFA) by Optimal Sphere Packing (OSP), which seeks filter positions that maximize the minimum distance between the spheres's centers. The proposed design reduce reconstruction artifacts even when using conventional demosaicking algorithms and Neural Network. Furthermore, we compare our design with random (RND), Blue Noise (BN), Interuniversity Microelectronics Centre (IMEC) and binary tree-based edge-sensing (BTES). For the experiments, we use real spectral filter responses of the IMEC MSFA of the Ximea camera.

Discrete Model

The acquisition of the spectral mosaic image projection of L spectral bands is

$$\mathbf{Y} = \sum_{l=1}^{L} \mathbf{X}_l \odot \mathbf{C}_l + \mathbf{\Omega}, \qquad (1)$$

where $\mathbf{X}_l \in \mathbb{R}^{M\times N}$ is the l^{th} spectral band of the datacube with $M \times N$ number of pixels, $\mathbf{C}_l \in [0,1]^{M\times N}$ is the coded aperture and $\mathbf{\Omega} \in \mathbb{R}^{M\times N}$ is the Gaussian noise, the design of our MSFA-OSP can benefit from the following solution for the placement of the spheres within a kernel $\mathbf{B}$ as follows

$$\mathbf{B} = ((a \odot \mathbf{I} + b \odot \mathbf{J}) \mod L) + \mathbf{1}, \qquad (2)$$

$\mathbf{I} = \mathbf{g}^T \otimes \mathbf{q}$ such that $\mathbf{I} \in \mathbb{N}^{L\times L}$, being $\mathbf{g}$ a vector of all ones such as $\mathbf{g} \in \{1\}^L$, and $\mathbf{q} = [1,\ldots,L]^T$ such as $\mathbf{q} \in \mathbb{N}^L$ $\mathbf{J} = \mathbf{I}^T$, $\mathbf{1} \in \mathbb{N}^{L\times L}$, $s,t \in \{1,\ldots,L\}$ Thus, the distance between a set of V spheres is given by

$$d^*(V) = \max(\min_{1\le k_1<k_2\le V} D_{k_1,k_2}), \qquad (3)$$

where $k_1, k_2 \in \{1,\ldots,V\}$, such that $V = L^2$, $D_{k_1,k_2} = \|\mathbf{p}_{k_1} - \mathbf{p}_{k_2}\|_2^2$ is the all pairwise distance matrix, the theoretical upper bound SP density for the optimal MSFA as

$$\rho^*(V) = 2\sqrt[3]{\frac{(\sqrt{V}+1)^3}{4V\sqrt{2}}}, \qquad (4)$$

being the OSP density is $\rho_{\Lambda_3} = \frac{\pi}{\sqrt{18}} \approx 0.74$.

• **Theorem:** *No packing of congruent balls in Euclidean three space has a density greater than that of the face-centered cubic packing* Λ_3.

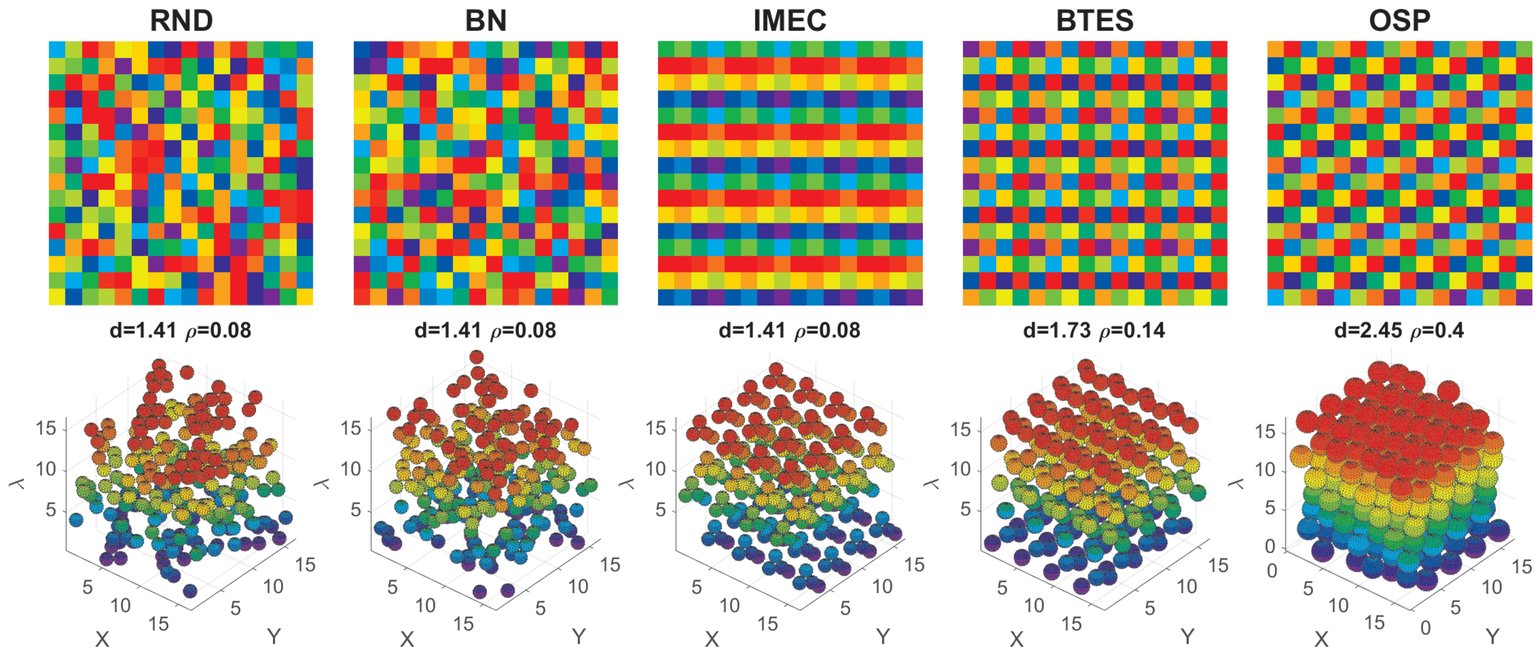
Funding

ANID DOCTORADO NACIONAL (2023-21231970); SPS ICASSP 2024 Grant; ANID ANILLOS (ATE220022); ANID FONDECYT (1221883, 1241149, Postdoctorado 3230489)

Bibliography

[1] T. C. Hales, "A proof of the kepler conjecture," Annals of mathematics, vol. 162, no. 3, 2005.
[2] E. Vera, F. Guzman, and N. Diaz, "Shuffled rolling shutter for snapshot temporal imaging," Opt. Express, vol. 30, no. 2, Jan 2022.
[3] E. Vera, F. Guzman, and N. Diaz, 'Shuffled Rolling Shutter Camera', in Coded Optical Imaging, J. Liang, Springer International Publishing, 2024.

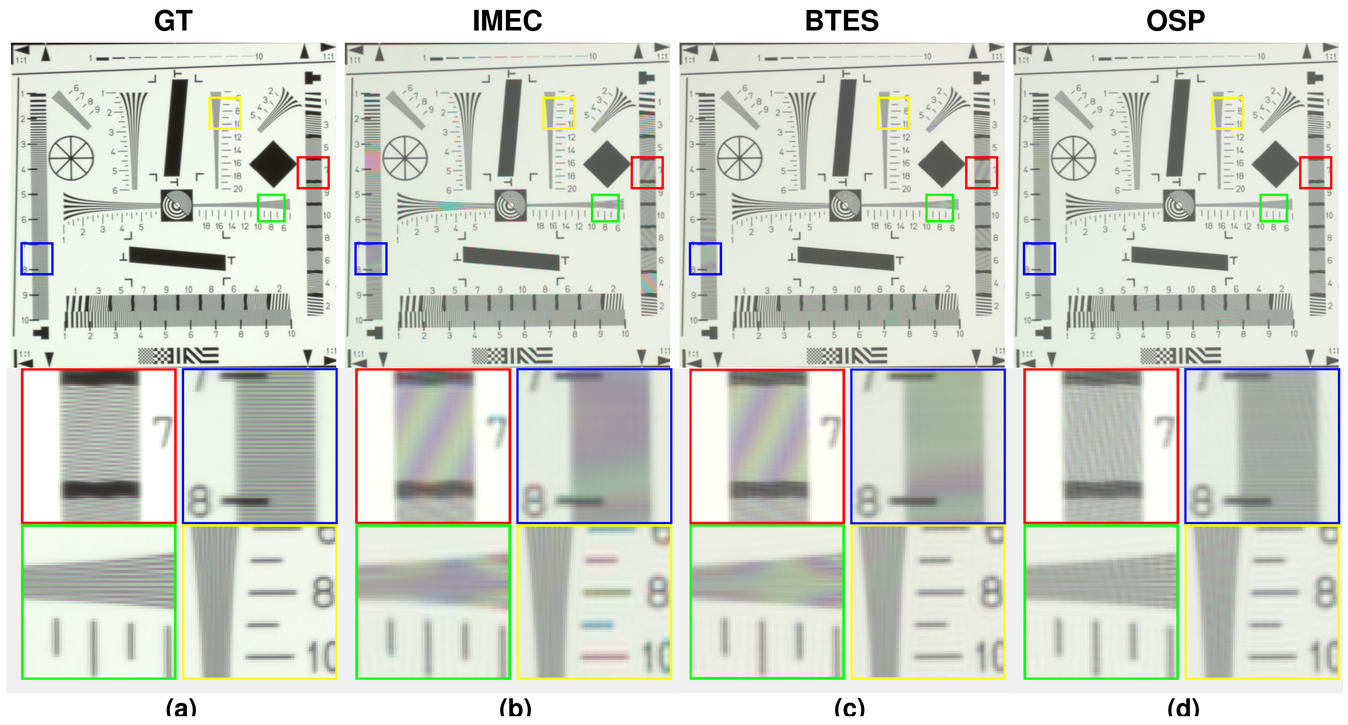
Method



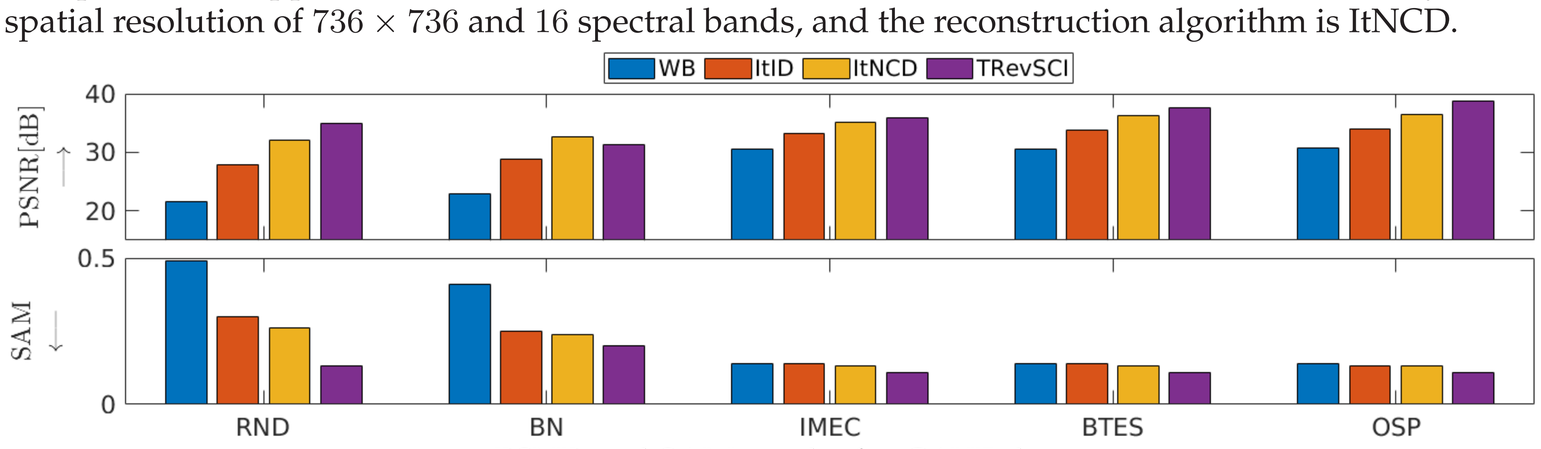
Comparison between MSFAs with spatial resolution 16×16, and spectral resolution 16.

Results

Simulations

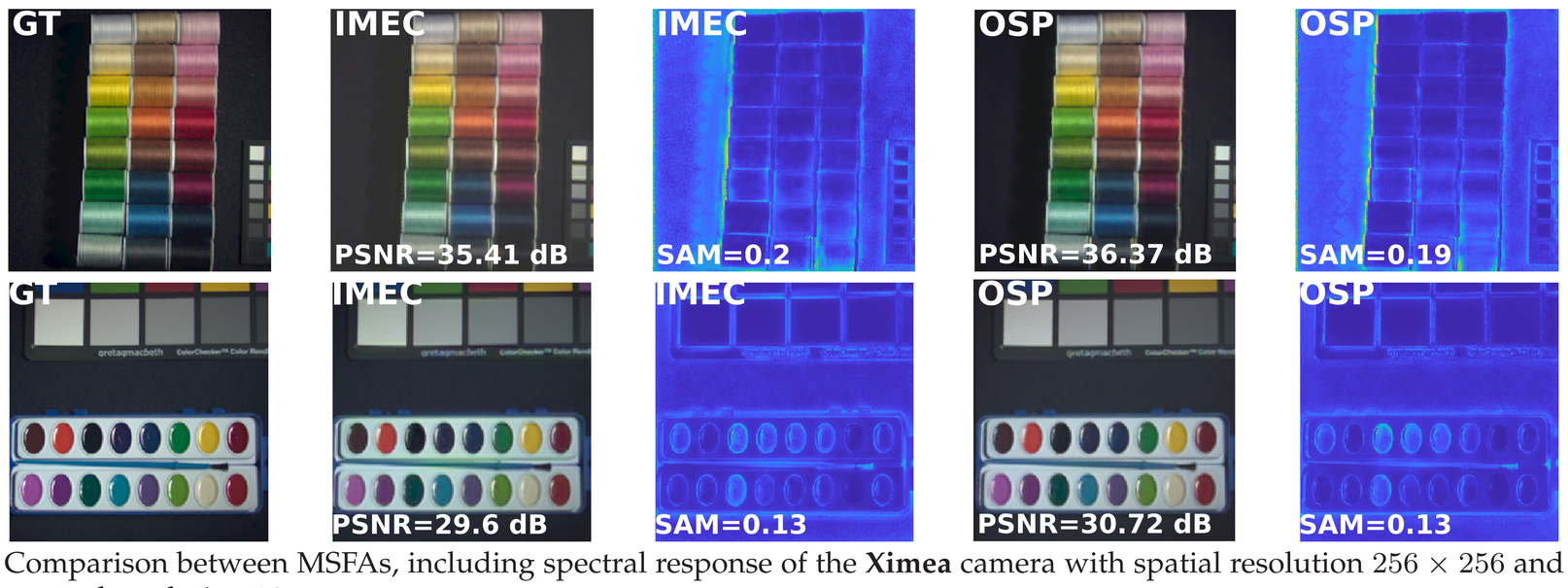


Comparison of Zipper effect and color distortion between three MSFAs. The chart scene of Tokyotech has a spatial resolution of 736×736 and 16 spectral bands, and the reconstruction algorithm is ItNCD.



PSNR and SAM results for CAVE dataset.

Experiments with real filters



Comparison between MSFAs, including spectral response of the **Ximea** camera with spatial resolution 256×256 and spectral resolution 16.

Conclusions

• The advantages of Optimal Sphere Packing include reducing artifacts such as false colors and the zipper effect of demosaicking algorithms.