Multiplexed Multispectral Filter Array by 3D Sphere Packing Design

Alejandro Alvarado[1], Nelson Díaz[1], Pablo Meza[2], and Esteban Vera[1,*]

[1] *School of Electrical Engineering, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile*
[2] *Department of Electrical Engineering, Universidad de la Frontera, Temuco, Chile*
[*] *esteban.vera@pucv.cl*

Abstract: We extended the 3D-Sphere Packing to design a Multiplexed Multispectral Filter Array that increases the measurement signal-to-noise ratio and allows an increase in the of number bands, approaching the resolutions expected for hyperspectral imaging systems.

1. Introduction

Spectral Imaging (SI) is a technique used in many areas, with a myriad of examples in remote sensing, medicine and environmental monitoring. This technique allows the acquisition of spatio-spectral information in three-dimensions, known as datacubes. Moreover, SI is classified in two groups according to the spectral resolution, the first is multispectral imaging (discrete spectra)–where an example is the multispectral filter array (MSFA) [1]–and the second is hyperspectral imaging (continuous spectra). Nevertheless, a MSFA is an extension of the Bayer filter [2] and it is typically constrained by the number of achievable resolving bands. Furthermore, the poor signal-to-noise ratio (SNR) when the number of spectral bands is increased is one of the biggest hurdles in SI. On the other hand, a clear benefit of MSFA is the snapshot nature of the acquisition without requiring spatial scanning nor a filter wheel. Meanwhile, in hyperspectral imaging the limitations are the complex optical systems and the time-consuming scanning mechanisms [3], unless compressive approaches are employed [4].

However, multiplexing bands to extend the design of MSFA towards a Multiplexed Multispectral Filter Array (MMSFA) can improve the measurement signal-to-noise ratio (SNR). In this way, the design of a Multiplexed Multispectral Filter Array (MMSFA) can be considered as coded aperture design problem, where the multiplex bandpass filters per pixel are indicated by their position within the datacube. In this paper, we propose a 3D Sphere Packing [5, 6] approach to design the positions of the sampled bandpass filters at the different measured pixel positions in the sensor plane, enforcing the maximum separation between the central wavelength of the chosen bandpass filters.

2. Method

The sphere packing approach promotes the optimization of the distance between the spheres d to optimize the density of spheres ρ in the container, where a higher density is related with a better sampling. The main idea is to extend the 3D Optimal Sphere Packing (OSP) [7, 8] to increase the number of the spheres within the cubic container; this approach increases the transmittance of the Coded Aperture (CA) and allows the sampling of a higher number of bands approaching to the spectral resolution of hyperspectral systems. The reader can notice the lower transmittance of MSFA against the higher transmittance of the MMSFA. Figure 1(a) and 1(b) show CAs with kernels to sample 16 bands. In the first CA the transmittance is $\frac{1}{16}$ since the design solely uses bandpass filters. In contrast, in the second CA the transmittance is $\frac{3}{16}$, due to the chosen multiplexing. In addition, figure 1(b) and 1(d) are represented by the samples selected by the CA using a sphere packing representation within the full wavelength range.

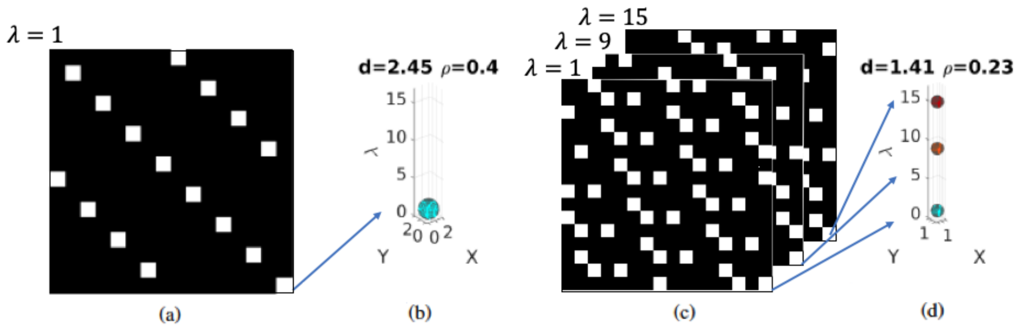

Fig. 1: Coded aperture and sphere representation: (a) CA, 1st band for no-multiplexed filters, (b) Sphere representation in 1 pixel for 1(a), (c) CA, 1st band for 3-multiplexed filters, (d) Sphere representation in 1 pixel for 1(b)

3. Simulation Results

We present a performance comparison between the proposed MMSFA design with a random multiplexed pattern. We used the CAVE dataset [9] with a spatial resolution of 256×256 pixels with 16 and 31 bands for our preliminar experiment. The evaluation includes a comparison of the proposed design with a random design using 3 and 5 multiplexed filters. Furthermore, we test all the dataset with GAP-TV [10], which was developed for compressive imaging reconstruction. The average Peak-Signal-to-Noise Ratio (PSNR) for all the dataset achieved by both MMSFAs are depicted in Table 1.

Bands	Random 3 Multiplexed Filters	SP 3 Multiplexed Filters	Random 5 Multiplexed Filters	SP 5 Multiplexed Filters
16	28.54[dB]	29.86[dB]	29.03[dB]	30.61[dB]
31	25.99[dB]	26.84[dB]	26.51[dB]	27.25[dB]

Table 1: PSNR for preliminary results using GAP-TV with 3 and 5 multiplexed bands.

Figure 2 depicts an example of a the scene "threads" with 16 bands and a spatial resolution of 256x256 pixels, where the advantages of our design are highlighted. Specifically, our design promotes a better reconstruction SNR than a random design while reducing the color artifacts and zipper effect.

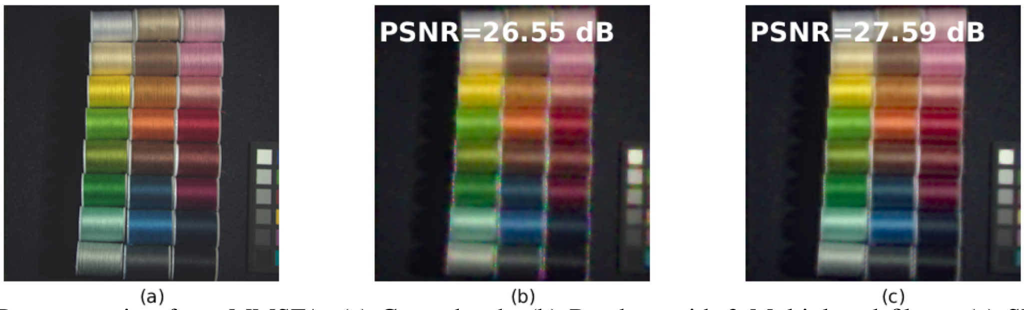

Fig. 2: Reconstruction from MMSFA: (a) Groundtruth; (b) Random with 3 Multiplexed filters; (c) SP with 3 Multiplexed filters.

4. Conclusions

We have extended the 3D optimal sphere packing approach to design a Multiplexed Multispectral Filter Array (MMSFA). Reconstruction results show promising results. We demonstrated that using the proposed design we were able to increase the number of bands without dramatically loosing in the measured SNR. We are working on a experimental demonstration of our new MMSFAs testing with a higher number of reconstructed spectral bands.

Funding

ANID DOCTORADO NACIONAL (2023-21231970); ANID ANILLOS (ATE220022); ANID FONDECYT (1221883, 1241149, Postdoctorado 3230489).

References

1. L. Miao, H. Qi, R. Ramanath, and W. Snyder, "Binary tree-based generic demosaicking algorithm for multispectral filter arrays," IEEE Trans. on Image Process. **15**, 3550–3558 (2006).
2. B. E. Bayer, "Color imaging array," United States Pat. 3,971,065 (1976).
3. L. Huang, R. Luo, X. Liu, and X. Hao, "Spectral imaging with deep learning," Light. Sci. & Appl. **11**, 61 (2022).
4. A. Wagadarikar, R. John, R. Willett, and D. Brady, "Single disperser design for coded aperture snapshot spectral imaging," Appl. Opt. **47**, B44–B51 (2008).
5. H. Cohn, "A conceptual breakthrough in sphere packing," Notices Am. Math. Soc. **64**, 102–115 (2017).
6. E. Vera, F. Guzmán, and N. Díaz, "Shuffled rolling shutter for snapshot temporal imaging," Opt. Express **30**, 887–901 (2022).
7. N. Diaz, A. Alvarado, P. Meza, F. Guzmán, and E. Vera, "Multispectral filter array design by optimal sphere packing," IEEE Trans. on Image Process. **32**, 3634–3649 (2023).
8. E. Vera, F. Guzman, and N. Diaz, *Shuffled Rolling Shutter Camera* (Springer International Publishing, Cham, 2024), pp. 499–513.
9. F. Yasuma, T. Mitsunaga, D. Iso, and S. Nayar, "Generalized Assorted Pixel Camera: Post-Capture Control of Resolution, Dynamic Range and Spectrum," Tech. rep. (2008).
10. X. Yuan, "Generalized alternating projection based total variation minimization for compressive sensing," in *2016 IEEE International Conference on Image Processing (ICIP),* (2016), pp. 2539–2543.