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# Computational image projection with extended depth-of-field and field-of-view: concept and implementations

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## 1. Introduction

Depth-of-field (DOF) and field-of-view (FOV) in image projection are restricted by three-dimensional (3D) aberrations. A standard method is to measure the 3D position of the screen before projection. Computational projection with phase modulation provides an effective solution for this problem. Under the concept of point spread function (PSF) engineering, the PSF is modified and post-processing is performed to enhance the property of imaging system. Based on this idea, a method for extended-DOF projection was proposed, which uses a cubic phase plate for depth-invariant PSF [1]. We developed the method for extension of both DOF and FOV with 3D space-invariant PSFs in image projection [2,3]. In this presentation, we introduce two implementations for the extended-DOF and -FOV projection and summarize their features.

## 2. Implementation with superposition compound-eye optics

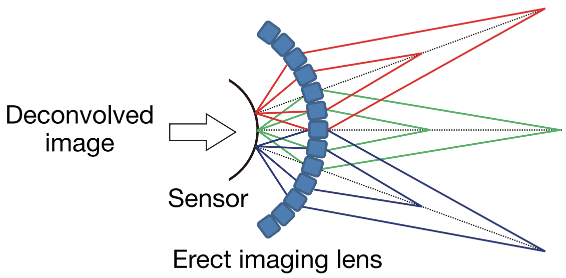


Fig. 1. Schematic of computational superposition projector.

Nocturnal insects are known to have superposition compound-eyes, which are composed of an array of small erect imaging optics, for bright imaging with thin optics. In our previous study, the superposition compound-eye optics was arranged on a spherical surface to implement 3D space-invariant PSF [2]. Schematic diagram of the proposed projection so-called *computational superposition projector* is shown in Fig. 1. The spherical erect lens array optically superposes images with different focusing distances on a screen, which averages depth-variant defocus in projection. Simultaneously, monocentric optics realizes an angle-invariant PSF. As a result, a 3D space-invariant PSF is achieved in image projection. The blur in a projected image by the PSF is compensated by deconvolution before the projection.

The authors have verified the proposed method using mechanical scan of an incoherent light projector. In the experiment, we chose the Richardson-Lucy method with a non-negative constraint as the deconvolution algorithm. Projection of a deep-focused image on an uncalibrated 3D screen was successfully demonstrated [2].

## 3. Implementation based on computational phase modulation

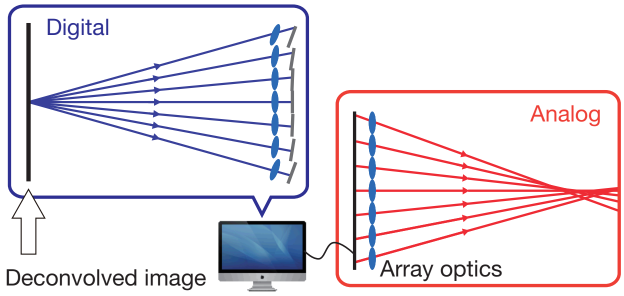


Fig. 2. Schematic of computational phase-modulation projector.

As a flexible and powerful framework of computational imaging, the authors proposed a computational phase modulation method [3]. The schematic diagram of the computational phase-modulation projector is shown in Fig. 2. In the method, the process of image projection is divided into two steps: computational 4D ray-projection by virtual array-optics and optical 4D ray-projection via physical array-optics, e.g. a convex lens array for projection. Phase modulation is computationally implemented in the virtual array-optics. We have verified superresolved extended-DOF projection using phase modulation based on the proposed method [3].

## 4. Features of two implementations

The main difference between two implementations is the method to realize phase modulation. The advantages of the optical approach are simplicity, speed, and image quality of a total projection system. On the other hand, the merit of the computational approach is high flexibility for implementing phase modulation, which means that it can realize arbitrary phase modulation only by changing computational algorithms. The optimal choice of the implementation method depends on the tolerance to the cost of optical elements and computational complexity in applications.

## References

[1] W. T. Cathey and E. R. Dowski, U.S. patent 6,069,738 (2000).
[2] T. Nakamura *et al*., Opt. Lett. **38**, 1560-1562 (2013).
[3] T. Nakamura *et al*., Opt. Express **21**, 29523-29543 (2013).