Title	Computational lensless imaging utilizing aggressive design of coded optical systems
Author(s)	Nakamura, Tomoya
Citation	Proceedings of SPIE - The International Society for Optical Engineering. 2025, 13610, p. 1361004
Version Type	VoR
URL	https://hdl.handle.net/11094/103620
rights	© 2025 SPIE.
Note	

Invited Paper

Computational lensless imaging utilizing aggressive design of coded optical systems

Tomoya Nakamura[a]

[a]Graduate School of Engineering Science, The University of Osaka, 1-3 Machikaneyama, Toyonaka, Osaka, Japan

ABSTRACT

Computational lensless imaging reconstructs images from coded measurements without using lenses and offers advantages such as compactness, low cost, and lightweight implementation. While much of the existing research has focused on algorithmic reconstruction, optical design plays a crucial role in determining the quality and robustness of the reconstructed images. In this work, I introduce two optical coding strategies that extend the capabilities of lensless imaging systems beyond conventional designs. The first approach achieves extended depth-of-field (EDOF) imaging by designing a coded mask that generates a radially invariant point spread function (PSF), enabling simultaneous reconstruction of near and far objects. The second approach introduces a multi-layer mask architecture that utilizes the degrees of freedom along the optical axis to jointly optimize diffraction and angular resolution. We validate both methods through simulations and optical experiments, demonstrating improved reconstruction quality and reduced condition numbers. These results show that aggressive optical design can significantly enhance lensless imaging performance, while also introducing new challenges such as increased computational cost and loss of shift-invariance. Our findings suggest promising directions for future lensless camera development that balances optical complexity with computational efficiency.

Keywords: Lensless imaging, Computational imaging, Coded optical system

1. INTRODUCTION

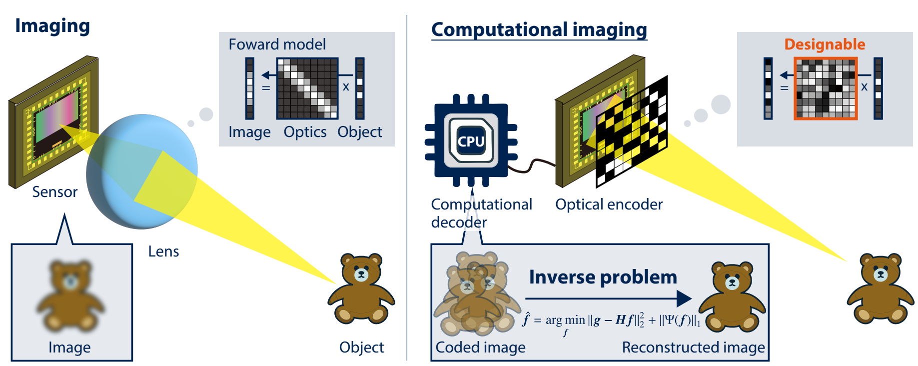

Figure 1. Schematic diagram of computational imaging.

Computational imaging (CI) is a technique that reconstructs images from coded measurements using computational algorithms (Fig.1). CI has attracted significant attention in recent years because it can overcome the limitations of conventional imaging systems by jointly designing the optical system and the reconstruction algorithm. CI has been applied to a variety of fields, such as microscopy,[1] cytology,[2] and holography.[3] Computational lensless imaging is a type of CI technique that reconstructs images from coded measurements without using lenses.[4] Lensless imaging offers several advantages over conventional imaging systems, including compactness, light weight, and low cost. These advantages make lensless imaging suitable for applications where size, weight, and cost are critical, such as in portable devices and medical imaging.[5]

Further author information: (Send correspondence to T.N.)
T.N.: E-mail: t.nakamura.opt@osaka-u.ac.jp, Telephone: +81 6 6850 6371

ODS 2025: Industrial Optical Devices and Systems, edited by Yuzuru Takashima, Kazuyoshi Yamazaki,
Proc. of SPIE Vol. 13610, 1361004 · 2025 Published by SPIE
0277-786X · doi: 10.1117/12.3063736

In research on computational lensless imaging, much of the focus has been placed on the design of reconstruction algorithms. While there have also been numerous studies on the design of coded optical systems,[6–8] they are relatively fewer in number. Nevertheless, the design of the coded optical system plays a crucial role in the overall performance of lensless imaging systems. The coded optics determine the quality of the measurements, which directly impacts the effectiveness of the reconstruction algorithm. Therefore, it is essential to consider optical design in conjunction with the reconstruction process.

In this manuscript, we focus on the aggressive design of coded optical systems for computational lensless imaging. Specifically, we introduce two approaches that exploit the design flexibility enabled by lensless architectures: (1) extended depth-of-field lensless imaging using a radial point spread function (PSF),[9] and (2) lensless imaging with multi-layer masks.[10] These methods highlight how optical coding strategies can be pushed beyond conventional designs to enhance imaging capabilities.

2. EXTENDED DEPTH-OF-FIELD LENSLESS IMAGING USING RADIAL PSF

In coded optical systems, as long as the stability of the inverse problem is ensured, there is significant flexibility in optical design. This design freedom can be intentionally exploited when optimizing for specific imaging parameters. In the case of two-dimensional imaging alone, one only needs to consider maximizing the optical transfer function and light efficiency, making random masks suitable choices. However, when depth-of-field (DOF), image quality, or reconstruction speed is of greater importance, it becomes necessary to design the coding system accordingly.

In a lensless coded optical system, the depth dependence of the PSF appears as radial scaling. If the scaling parameter of the PSF used during calibration does not match the one assumed during reconstruction, the resulting image will appear blurred or degraded. The tolerance to such PSF mismatch depends on the correlation between the scaled PSFs. In other words, the permissible distance error in lensless reconstruction–namely, the DOF–is determined by the PSF design. Put differently, if one can design a coded mask that generates PSFs invariant to radial scaling, it becomes possible to reconstruct sharp images of objects located at arbitrary distances.

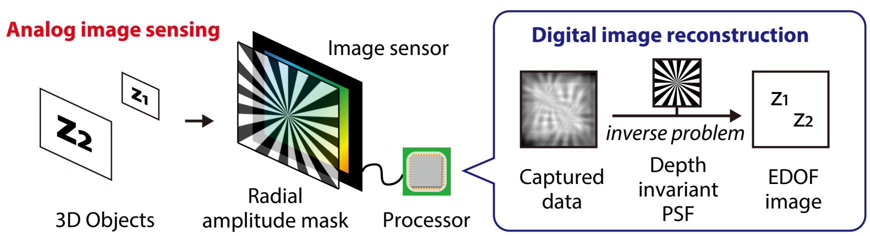

Figure 2. Schematic diagram of EDOF lensless imaging.

Based on this idea, we proposed a lensless imaging system with extended DOF (EDOF) using a radial aperture for optical encoding.[9,11] A conceptual diagram is shown in Fig. 2. By designing the coded mask with a radially invariant pattern–similar to a star chart–the resulting PSF becomes independent of object distance. To achieve EDOF, only radial invariance is necessary; the angular direction remains a degree of freedom. In a past work,[9] we optimized the angular component of the radial mask to maximize the integrated frequency response of the optical transfer function, while preserving radial invariance. This resulted in a mask with angular randomness.

Figure 3 presents experimental results. The coded mask was implemented using a transmissive liquid crystal spatial light modulator combined with polarizers. A lensless coded optical system was then constructed by integrating this mask with a board-level camera. Reflective diffuse objects were placed at both near and far distances from the camera, and their light was measured. The PSF was calibrated by imaging a point light source. Image reconstruction was performed using both ADMM[12] and DIP[13] methods.

The PSF used in reconstruction was calibrated at the far object distance. As shown in Fig. 3, with a conventional random mask, the front object appears blurred and the strokes of the letters "O" cannot be clearly resolved. In contrast, with the proposed optimized radial mask, both near and far objects are simultaneously in

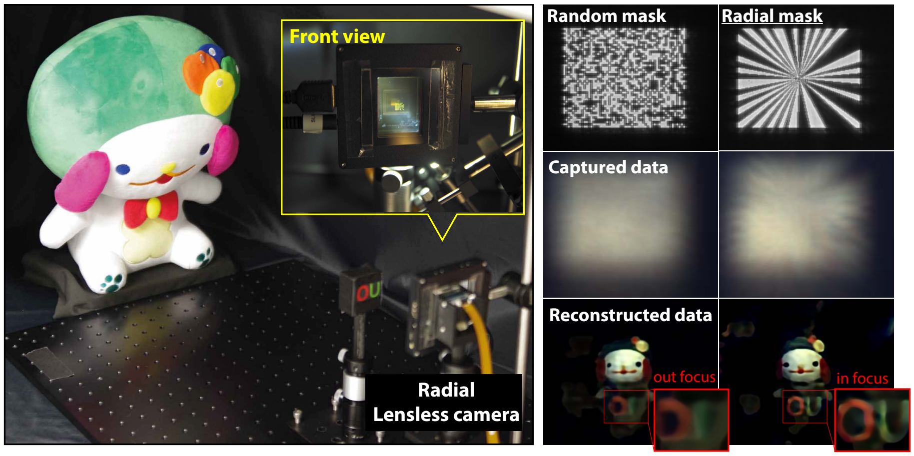

Figure 3. Experimental demonstration of EDOF lensless imaging.

focus, and the strokes of "OU" are clearly separated and identifiable. For further details, including comparisons with other masks, the impact of pattern optimization, quantitative evaluations, and experiments with objects having continuous depth, please refer to the paper.[9]

3. LENSLESS IMAGING WITH MULTI-LAYER MASKS

In lensless cameras, it is common to design the optical system using a single coded mask. However, coded optics inherently have degrees of freedom along the optical axis as well. Here, we consider how the distance between the coded mask and the image sensor affects imaging performance. Reducing the distance suppresses diffraction blur, which is proportional to the propagation distance, thereby improving the optical resolution of the PSF. However, this comes at the cost of reduced angular sampling resolution, as the system becomes wider-angle. As a result, there exists a unique optimal distance that maximizes image clarity.[14]

If a lensless coded optical system could incorporate both a near-field mask (wide-angle) and a far-field mask (telephoto) simultaneously, and if the resulting multiplexed image could be measured, it would be possible to independently maximize both optical and angular sampling resolution. This would in turn enhance the overall imaging performance of the lensless camera.

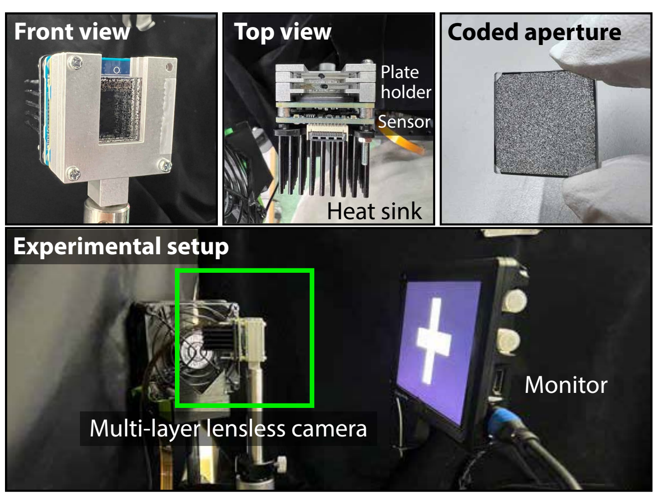

Figure 4. Experimental setup of a multi-layer lensless camera.

In a paper,[10] the difference in imaging performance between a single-layer and multi-layer coded mask configuration was investigated under the constraint of fixed overall system thickness and optical throughput.

Simulations were implemented using ray tracing that accounts for diffraction blur. For the actual camera system, a mechanical jig was fabricated to align and fix multiple coded masks and a board-level camera into a composite system. The experimental setup is shown in Fig. 4.

The coded masks were fabricated by depositing chromium on synthetic quartz glass, followed by photolithography. Compared to spatial light modulators, lithographically fabricated masks offer fixed modulation patterns but can achieve spatial resolutions on the order of 1 m, and are free from limitations such as polarization dependency, incident angle sensitivity, and fill factor constraints.

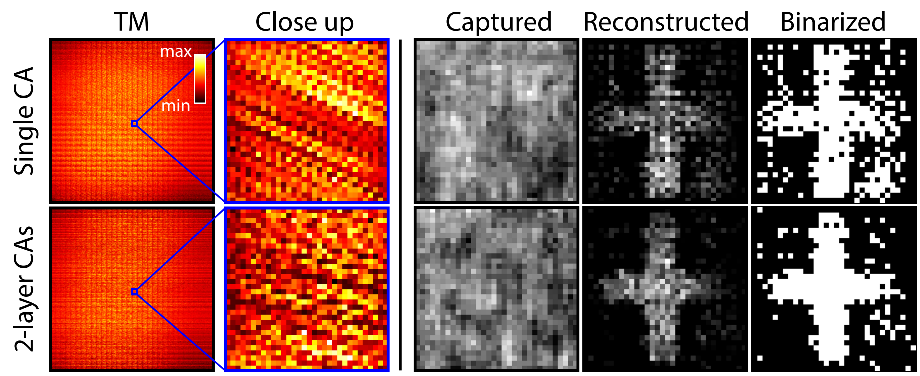

Figure 5. Experimental results of a multi-layer lensless camera.

Through both simulation and physical experiments, the transmission matrix (TM), representing the measurement process, was evaluated, and its condition number was computed. Results showed that the multi-layer system achieved a lower condition number compared to the single-layer system. Furthermore, coded imaging and image reconstruction were performed using the experimental setup in Fig. 4 to evaluate improvements in imaging performance. Results are shown in Fig. 5.

Since ground-truth luminance could not be used for quantitative evaluation in the optical experiment, binary test patterns were used as subjects. After reconstruction, binarization was applied using the known black-white pixel ratio, and the agreement rate with the input binary image was computed. As a result, in addition to qualitative improvements in reconstructed image quality, the agreement rate improved from 0.77 to 0.81, quantitatively demonstrating that multi-layer coding contributes to enhanced imaging performance. For further details and quantitative evaluations, refer to a paper.[9]

These findings confirm that multi-layer coded optics can improve imaging characteristics in terms of condition number and reconstruction quality. However, introducing multi-layer design breaks the shift-invariance property of the forward model. While such multi-layer architectures expand the design space and offer potential for improved performance, they also demand large-scale matrix computations during image reconstruction. This significantly increases the spatial and temporal computational cost. Therefore, to achieve practical high-resolution lensless imaging, further research is needed on accelerating both the computation and calibration of large-scale models.

4. CONCLUSIONS

In this manuscript, I explored advanced optical design strategies for computational lensless imaging, focusing on approaches that go beyond conventional single-layer, randomized-coded masks. I introduced two techniques that leverage the inherent design flexibility of lensless imaging systems: (1) EDOF imaging using a depth-invariant PSF, and (2) multi-layer mask architectures that utilize the optical axis to balance diffraction and angular resolution.

The first method demonstrated that radial invariance in the PSF enables robust image reconstruction across a wide range of object distances. By optimizing the angular structure of a radially invariant mask, we achieved clear and simultaneous imaging of both near and far objects, as validated through optical experiments.

The second method proposed a multi-layer coded mask design to overcome the trade-off between optical resolution and angular sampling inherent in single-layer systems. Simulation and experimental results confirmed that this design leads to improved imaging performance, as evidenced by a reduced condition number of the system matrix and higher reconstruction accuracy.

Together, these approaches illustrate how aggressive optical coding can significantly enhance the imaging capabilities of lensless systems. At the same time, they highlight new challenges: radially invariant masks impose design constraints in the radial domain, while multi-layer architectures increase model complexity and computational cost. Future work should focus on scalable calibration techniques, efficient reconstruction algorithms, and hybrid optical-electronic co-design to realize practical, high-performance lensless imaging systems.

ACKNOWLEDGMENTS

This work was supported by the JSPS KAKENHI (22H01992) and JST FOREST (JPMJFR206K).

REFERENCES

[1] Orth, A., Tomaszewski, M. J., Ghosh, R. N., and Schonbrun, E., "Gigapixel multispectral microscopy," *Optica* **2**(7), 654–662 (2015).

[2] Ota, S., Horisaki, R., Kawamura, Y., Ugawa, M., Sato, I., Hashimoto, K., Kamesawa, R., Setoyama, K., Yamaguchi, S., Fujiu, K., Waki, K., and Noji, H., "Ghost cytometry," *Science* **360**(6394), 1246–1251 (2018).

[3] Brady, D. J., Choi, K., Marks, D. L., Horisaki, R., and Lim, S., "Compressive Holography," *Optics Express* **17**, 13040–13049 (jul 2009).

[4] Boominathan, V., Robinson, J. T., Waller, L., and Veeraraghavan, A., "Recent advances in lensless imaging," *Optica* **9**, 1–16 (jan 2022).

[5] Asif, M. S., Ayremlou, A., Sankaranarayanan, A., Veeraraghavan, A., and Baraniuk, R. G., "FlatCam: Thin, Lensless Cameras Using Coded Aperture and Computation," *IEEE Transactions on Computational Imaging* **3**(3), 384–397 (2016).

[6] Stork, D. G. and Gill, P. R., "Lensless Ultra-Miniature CMOS Computational Imagers and Sensors," in [*The Seventh International Conference on Sensor Technologies and Applications*], 186–190 (2013).

[7] Shimano, T., Nakamura, Y., Tajima, K., Sao, M., and Hoshizawa, T., "Lensless light-field imaging with Fresnel zone aperture: quasi-coherent coding," *Applied Optics* **57**(11), 2841–2850 (2018).

[8] Nakamura, T., Watanabe, T., Igarashi, S., Chen, X., Tajima, K., Yamaguchi, K., Shimano, T., and Yamaguchi, M., "Superresolved image reconstruction in FZA lensless camera by color-channel synthesis," *Optics Express* **28**, 39137–39155 (dec 2020).

[9] Silva Neto, J. R. C. S. A. V., Nakamura, T., Makihara, Y., and Yagi, Y., "Extended Depth-of-Field Lensless Imaging Using an Optimized Radial Mask," *IEEE Transactions on Computational Imaging* **9**(3), 857–868 (2023).

[10] Nakamura, T., Kato, R., Iwata, K., Makihara, Y., and Yagi, Y., "Multilayer lensless camera for improving the condition number," *Applied Optics* **63**, G9–G17 (oct 2024).

[11] Nakamura, T., Igarashi, S., Torashima, S., and Yamaguchi, M., "Extended depth-of-field lensless camera using a radial amplitude mask," in [*Imaging and Applied Optics Congress*], CW3B.2, OSA, Washington, D.C. (2020).

[12] Antipa, N., Kuo, G., Reinhard, H., Mildenhall, B., Bostan, E., Ng, R., and Waller, L., "DiffuserCam: lensless single-exposure 3D imaging," *Optica* **5**(1), 1–9 (2018).

[13] Monakhova, K., Tran, V., Kuo, G., and Waller, L., "Untrained networks for compressive lensless photography," *Optics Express* **29**(13), 20913–20929 (2021).

[14] Nakamura, T., Kagawa, K., Torashima, S., and Yamaguchi, M., "Super Field-of-View Lensless Camera by Coded Image Sensors," *Sensors* **19**(6), 1329 (2019).