Computational lensless imaging using coded optics

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Abstract Computational lensless imaging is an imaging technique in which the lens system in a normal imaging system is replaced by a thin encoded optical element. Although it requires image reconstruction processing, it realizes a thinner, higher-performance, and higher-functional imaging system. In this talk, I will introduce our research on computational lensless imaging.

Keywords: Indirect Lensless imaging, Image reconstruction

1. Introduction

Imaging techniques based on the cooperative design of optical systems and signal processing systems are called computational imaging, and have been actively studied against the background of rapid progress in computer and information science in recent years. Among them, optical imaging techniques using lensless optical systems are called computational lensless imaging, and have been attracting attention as a technology to realize thinner optical systems [1].

Optical design in general imaging systems is based on the assumption of optical image formation and consists of a combination of imaging optics using lenses, concave mirrors, Fresnel zone plates, etc., and an image sensor. Optical design is based on the assumption that an optical image of an object is formed on the image-sensor device, and a visually good image can be obtained if aberrations are well suppressed in the system. On the other hand, because physical focusing is assumed, there is always a thickness of back focus in the optical design.

Optical design in computational lensless imaging does not assume optical image formation, so the optical design can be made thinner. Instead, an image reconstruction process is required. Image reconstruction is achieved by solving the inverse problem of image capture. It is important to note that the input-output response of the optical system is linear in intensity under incoherent illumination [2]. This allows quantitative evaluation of various properties of the inverse problem, such as stability and uniqueness of the solution, using knowledge of linear algebra. In addition, there are many established methodologies for solving the problem, ranging from direct methods such as the pseudo-inverse method to iterative methods such as the gradient descent method. As a result, computational lensless imaging has been proven to work in many real-world environments, thanks in part to the synergistic effects of recent advances in computer performance.

Computational lensless imaging has clear advantages in terms of thinning optical design, as mentioned earlier, but it also has clear disadvantages, such as increased computational complexity due to the need for image reconstruction processing and noise amplification by solving a linear inverse problem with spatially dispersively recorded intensity information as input. Therefore, to suppress these problems, the design of the image reconstruction processing algorithm as well as the design of the encoding optics is also important. Furthermore, the active design of the encoding optical system is also important from the viewpoint of expanding the degree of freedom in the design of the point spread function (PSF) in lensless imaging. For example, application of compressive sensing is easily possible

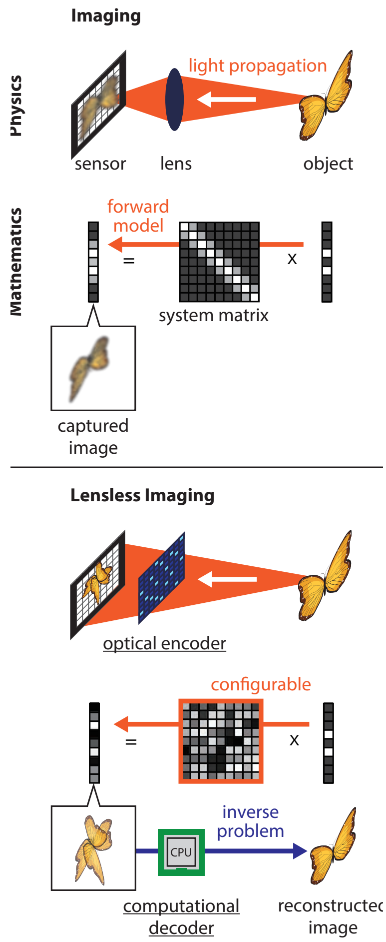

Fig. 1 Concept of computational lensless imaging.

in computational lensless imaging systems that is difficult in general lens-based imaging systems. This paper introduces research on computational lensless imaging (hereinafter referred to as "lensless imaging") that makes full use of active design of encoding.

2. Principle of lensless imaging

Lensless imaging is a technique to obtain a digital object image by measuring the coded image through the encoding optical system and inputting it to the decoding system [3]. Figure 1 shows a conceptual diagram. Coded optics plays the role of transmitting spatial information in computationally invertible form, i.e., lowering the condition number when the forward operation of the optical system is considered as a matrix. As an implementation method of coded optics, the coded aperture [4], used in synchrotron radiation imaging in the past, is often used. Not only the amplitude-modulation mask, phase-modulation masks [5] such as scatterers [6], diffractive optical elements [7], and randomly shaped mirrors [8] have also been used. These elements are implemented as fixed or dynamic elements by lithographic processing or the use of liquid crystals.

The forward model of coded measurement can most commonly be described in matrix form due to the linearity of the optical system. However, the resolution of recent image sensors is so large that it is impractical to explicitly keep a matrix, so it is often described in the form of a convolution operator with a PSF based on a shift-invariant approximation of the optical system. Therefore, the optical transfer function (OTF) of the optical system can be analyzed from the mask structure, and the quality of the optical system can be simply discussed in terms of frequency characteristics. This shows that random codes are an example of coding with good properties for imaging. In order to obtain even better frequency characteristics, methods have been proposed to increase the contrast and sparsity of the random code [5], and to combine multiple shots and phase-shifted image synthesis. In addition, because the PSF is structured and depth-dependent, three-dimensional (3D) information can be recovered after measurement as in the case of incoherent holography. Designs that maximize this 3D dependence have also been proposed [9].

In lensless imaging, image reconstruction is implemented by solving a linear inverse problem after measurement. The simplest way to do this is to apply an inverse filter, but there are issues such as the gap between the convolution approximation model and reality, noise tolerance, and so on. For this reason, methods such as the gradient descent method that minimize the loss function including reconstruction error and regularization term are frequently used in recent studies [4]. Recently, machine-learning-based reconstruction method [10] and speckle-correlation-based reconstruction method [11] are also used.

2. Integration with compressive sensing

A lensless imaging system consisting of an encoding mask and an image sensor can implement a PSF with spatial structure. By spatially randomizing the PSF, an optical system represented by a pseudo-random matrix can be implemented. Such an optical system is known to satisfy the conditions for realization of

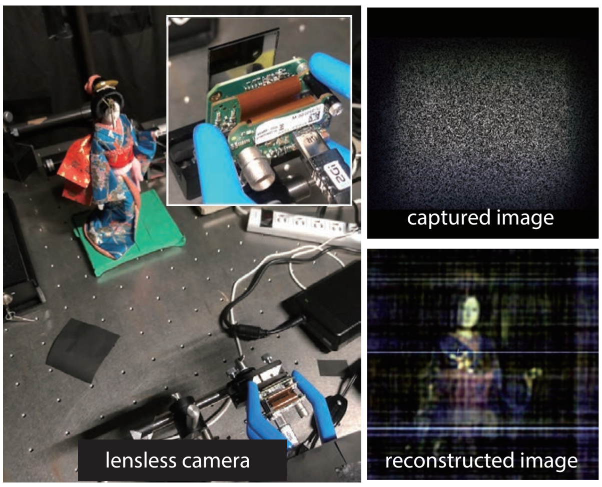

Fig. 2 Lensless imaging with compressive sensing.

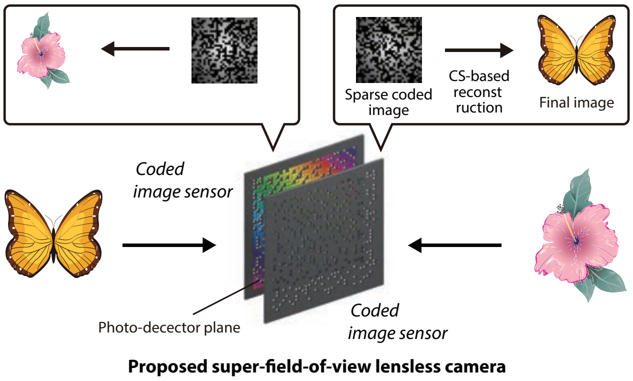

Fig. 3 Concept of wide-field-of-view lensless imaging with coded-apertured image sensors.

compressed sensing based on l_1-norm minimization [12]. Compressive sensing in imaging is a technique for numerically recovering dense object information from sparse observed data by solving a sparse-constrained linear inverse problem [13]. This enables reconstruction of a dense object image from a single image that contains many missing pixels.

The experimental optical system, imaging data, and reconstructed images are shown in Fig. 2 [14]. In the experimental optical system, a random encoding aperture was placed in front of a color CMOS image sensor (UI-3202SE-C by IDS). A spacing of 4.0 mm was provided between each element. The apertures were implemented by chromium deposition on glass. The specific design and optical parameters of the encoding aperture can be found in Ref [14]. The PSF required for the reconstruction process was obtained experimentally by measuring a point source. Pixel loss was simulated by randomly zeroing 50% of the pixels after measurement. 2D total variation (TV) was employed as a linear transformation for sparse constraints [15]. The TwIST method was used as an algorithm to minimize a non-differentiable cost function involving 2D TV [16]. It was experimentally demonstrated that the object image can be reconstructed from half of the measured image signal.

The above verification has led to the conclusion that at least half of the photodetectors in an image sensor are unnecessary in lensless imaging. Extending this idea, equivalent imaging can be implemented even if unnecessary pixels are apertured (perforated). This can be implemented in a CMOS image sensor by using a deep reactive ion etching (DRIE) [17]. We are studying a wide-field lensless imaging system by mounting multiple coded-apertured image sensors facing with each other. A conceptual diagram is shown in Fig. 3. In the proposed imaging system, the apertured image sensor functions as a coded aperture for the back side of the space viewed from the photosensor surface and as a sparse image sensor for the front side. This allows sparse encoded measurements of two opposing fields of view to be implemented in a single image capture, allowing simultaneous acquisition of object images from both fields of view via image reconstruction processing based on compressed sensing. We are currently working on the physical implementation of this imaging system.

3. Extension of depth of field

There is a degree of freedom in the design of codes implemented as PSFs. In particular, the frequency response directly affects the imaging characteristics, but flexible designs can be considered depending on the parameters for specific

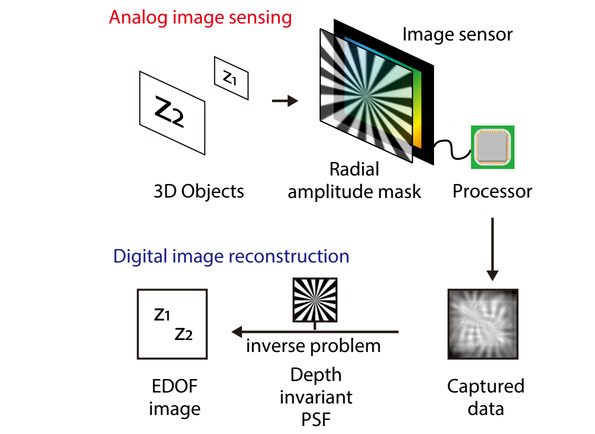

Fig. 4 Concept of extended depth-of-field lensless imaging.

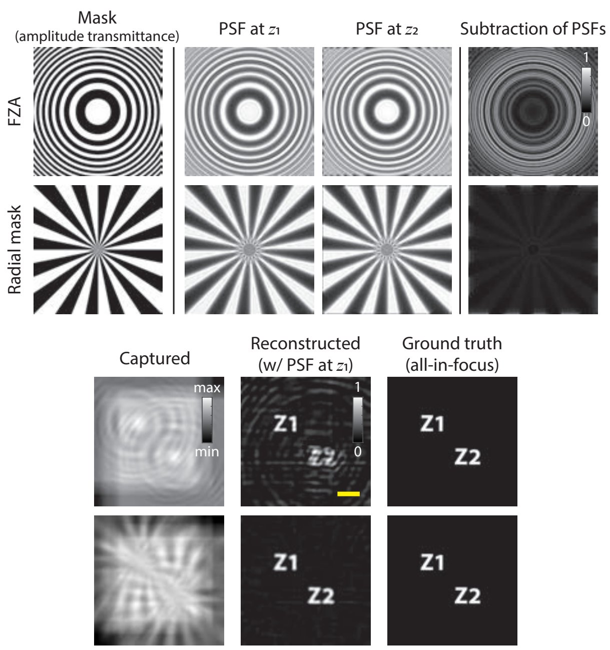

Fig. 5 PSFs, captured data, and reconstructed data using radial amplitude mask and Fresnel zone aperture.

measurement situations. We have proposed a coding aperture aimed at extending the depth of field of imaging [18]. A conceptual diagram of the proposed lensless imaging with extended depth of field is shown in Fig. 4. Since there is no focusing mechanism in lensless imaging, the depth dependence of the PSF is manifested as a scaling of its pattern in the radial direction [6]. Therefore, the PSF can be made depth-invariant by implementing the intensity transmittance pattern of the encoded aperture in the form of a radial structure. Existing methods assume that the 3D information of the object space is estimated directly or indirectly beforehand in order to obtain an extended depth-of-field or all-in-focus image [19]. Since the proposed method uses a depth-invariant PSF, it is possible to obtain an all-in-focus image with a single image reconstruction process using a single filter, instead of measuring or estimating 3D information of the object.

Numerical simulation results of the proposed method are shown in Fig. 5. In the simulation, a flat object (z1, z2) is assumed to exist at 100 mm and 1000 mm from the aperture plane, respectively, and the PSF from these distances is calculated by the angular spectrum method. 532 nm wavelength is assumed and the mask-to-sensor distance is 4.0 mm. As shown in Fig. 5, the depth dependence of the PSF was suppressed by the application of the radiation mask. The image data was generated by calculating the convolution of the object and the PSF at each distance and integrating it over two distances. The image was reconstructed using the TwIST method. The proposed method was able to reconstruct an image in focus at both distances simultaneously, whereas the existing method is naturally in focus at only one of the distance planes. For details of the method and results, please refer to Ref. [18].

4. Resolution improvement by color-channel synthesis

In lensless imaging, especially when the coded aperture is implemented as an intensity modulator, the PSF is geometrically approximated by its geometric projection. In wave optics, on the other hand, the PSF is a diffraction pattern of the encoding aperture. This diffraction causes blurring of the PSF, which is a factor in resolution reduction.

On the other hand, in the case of lensless imaging using a Fresnel zone aperture [20], the effect of this diffraction is manifested as a zero crossing of the OTF. The zero-crossing frequency is wavelength-dependent. Therefore, we have proposed a reconstruction method that implements deconvolution filtering by converting RGB color space to YCbCr color space, thereby avoiding the zero-crossing problem in the luminance channel and restoring signals up to the cutoff frequency [21]. The concept and simulation results are shown in Fig. 6. The existing method uses the geometric projection of the encoding aperture as a reconstruction filter, so the frequency information lost in the measurement process is not recovered and the reconstructed image is degraded. The proposed method recovers signals up to the cutoff frequency in the luminance channel by color space transformation with wave optics accuracy, resulting in a sharper reconstructed image. In the color-difference channel, the zero-crossing frequency information is not accurately reconstructed in principle, but the effect of image degradation and color distortion is small from the viewpoint of visibility by the human visual system.

Figure 7 shows an experimental system for proof of concept. A lensless imaging system is composed of an intensity mask and an image sensor, and the object to be measured is placed in front of the mask. For details of the optical system parameters, please

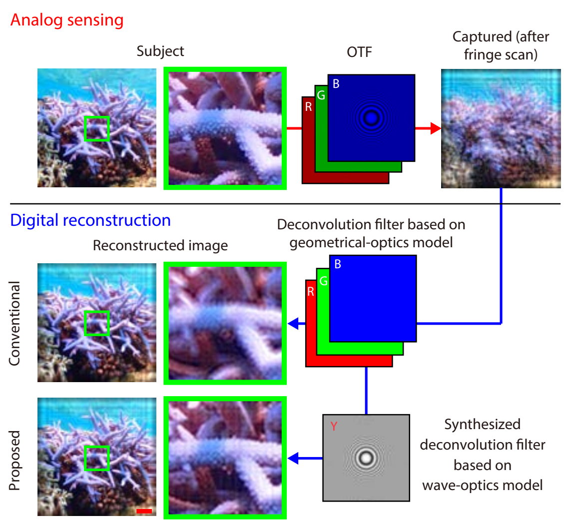

Fig. 6 Concept of high-resolution image reconstruction in lensless imaging by color-channel synthesis.

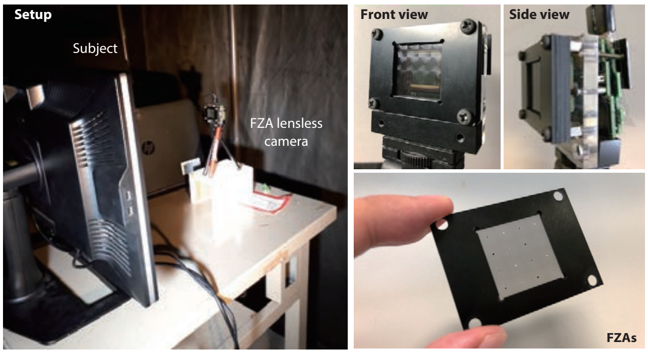

Fig. 7 Experimental setup.

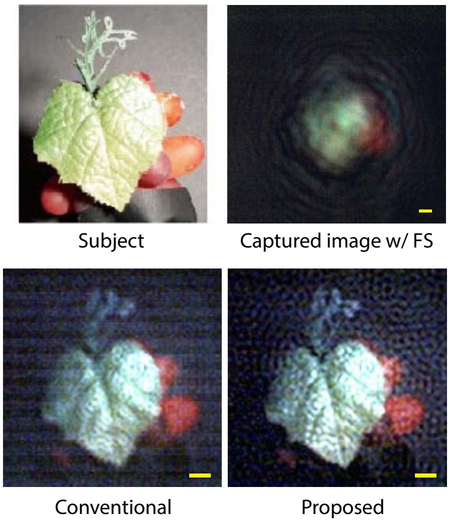

Fig. 8 Experimental results.

refer to Ref. [21]. The experimental results of imaging and reconstruction are shown in Fig. 8. The image data was post-processed based on the fringe-scan method [22], and the reconstruction process was implemented by deconvolution using a filter based on a geometric projection model for the conventional method, and by deconvolution using a color space transformation and a filter based on a wave model for the proposed method. The results show that the proposed method can reconstruct sharp images even when real objects are used in a real environment.

5. Conclusion

In this paper, I have outlined the technology and introduced our research results on computational lensless imaging with optical encoding. I emphasize that lensless imaging is not only useful for reducing the thickness of optical systems, but also for expanding the degree of freedom in designing computational imaging systems that incorporate optical encoding. On the other hand, existing research has focused on simplifying the optical system and has not fully utilized the design freedom of the encoded optical system. In other words, the combination of an image sensor and a single intensity- or phase-modulated encoding aperture is assumed, and active use of other optical dimensions, multilayering, recursion, nonlinearization, etc. have not been fully investigated. The increasing complexity of these coded optical systems is expected to lead to the introduction of advanced optical information processing mechanisms in camera hardware, leading to the creation of new intelligent optical imaging systems.

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