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Single-pixel holographic video camera

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Abstract: Optical scanning holography (OSH) can measure three-dimensional (3D) fluorescence targets by recording incoherent holograms with two-dimensional Fresnel zone pattern (FZP) scanning and a single-pixel detector. However, the complexity of the optical setup has limited its applicability. Computational OSH (COSH) has been proposed as a solution to this problem and has shown to be feasible with optical applications such as ghost imaging or Hadamard transform single-pixel imaging. However, the problem with FZP's scanning speed has limited its ability to visualize dynamic objects. In this study, dynamic objects were visualized using a high-speed digital micromirror device (DMD). In addition, a microscope based on COSH was constructed and then applied to capture moving images of dynamic objects behind dynamic scatterers. The experimental results show that the proposed method captures incoherent holograms with a frame rate of 1.387 Hz using a single-pixel detector. Moreover, numerical simulations indicate that the proposed method achieves imaging with a frame rate of approximately 28 Hz by using random sparse sampling and compressive sensing-based reconstruction.

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1. Introduction

Incoherent digital holography (IDH) [1,2] is attracting a lot of attention from researchers because it is possible to obtain a 3D distribution of targets using holograms with natural light or light by spontaneous emission. OSH is one of the methods to perform incoherent digital holography (IDH), together with Fresnel incoherent correlation holography (FINCH) [3]. OSH uses a single-pixel detector, similarly to other single-pixel imaging techniques, while FINCH employs a 2D pixelated image sensor. FINCH has been used in a variety of applications, including fluorescence microscopy [4], coherence measurements [5], and super-resolution microscopy [6]. Furthermore, according to the development of sophisticated optical systems, FINCH can capture 3D dynamic events [7–9]. However, the need for an image sensor makes it difficult to apply FINCH to non-visible wavelength conditions, mainly because pixelated sensors for the non-visible spectral range are not as easy to manufacture as they are for the visible range. In addition, FINCH requires adaptive optics in the presence of aberrations [10] and has never been applied to imaging through scattering media. In contrast, single-pixel imaging (SPI) is an advanced computational imaging technique that can be applied to light out of the visible spectral range and is more tolerant to aberration and scattering conditions. OSH, one of the SPI techniques, can obtain incoherent holograms of 3D fluorescence distribution with a single-pixel detector [11,12]. OSH have been applied to various applications such as fluorescence imaging [13,14], polarization imaging [15], multi-wavelength imaging [16], and quantitative phase

imaging [17,18], among others. In addition, SPI has been shown to be immune to the presence of scattering media between the modulator and the object [19] and tolerant if the turbid media is located between the object and the detector [20]. Taking advantage of these properties, OSH has already obtained incoherent holograms of a 3D object behind scattering media [21,22]. In general, OSH requires a two-path interferometer to generate interference patterns for illumination; therefore, the optical setup of OSH is complicated. To overcome the complexity, computational OSH (COSH) has been proposed [23–27]. By using a spatial light modulator (SLM), COSH can achieve a common-path interferometric optical setup. The measurement time of COSH is limited by the number of illumination patterns and the refresh rate of an SLM. In motionless OSH (MOSH), that uses a liquid crystal type SLM [23], the measurement time is about 5 minutes for 128×128 resolutions because the refresh rate of a liquid crystal type SLM is 60 Hz. Although subsampling techniques can reduce the measurement time, the speed is still limited by the refresh rate of liquid crystal SLMs [28,29]. Therefore, COSH cannot observe practical dynamic events compared with FINCH.

In this paper, we propose using a high-speed SLM, a digital micromirror device (DMD) with a refresh rate of 22 kHz, for COSH to observe dynamic events. Although a DMD has already been applied to COSH, termed interferenceless OSH (IOSH), dynamic events have never been measured due to its low refresh rate [26]. The results of proof-of-principle experiments indicate that the proposed method can be applied to 3D dynamic conditions. In addition, the proposed method is applied to microscopy and imaging through scattering media. Preliminary results of this work have been presented at a conference [30].

2. Principle

The basic principle of COSH is briefly introduced next. The detailed explanation can be seen in Ref. [27]. A schematic diagram of COSH with a DMD is shown in Fig. 1. By displaying FZPs with different center positions sequentially, intensity signals can be obtained by a single-pixel detector. By allocating the detected intensity signal according to the center position of FZPs, a hologram is obtained. The obtained hologram is described as follows:

$$I_\phi(x, y) = \int_z o(x, y; z) \otimes \text{FZP}_\phi(x, y; z) dz, \quad (1)$$

where $o(x, y; z)$ is the amplitude transmittance of the object, " $\otimes$ " is the operator of 2D convolution, and $\text{FZP}_\phi(x, y; z)$ is described as follows:

$$\text{FZP}_\phi(x, y; z) = \frac{1}{2} \left\{ 1 + \cos \left\{ \frac{k}{2z} (x^2 + y^2) + \phi \right\} \right\}, \quad (2)$$

where k and ϕ are the wavenumber and the bias phase of the spherical phase distributions, respectively. Our approach uses binarized FZPs for illumination patterns to use the maximum refresh rate of a DMD. The mean values of FZPs are used as the thresholds. By using a phase-shifting technique, a complex hologram $H(x, y)$ can be obtained as follows:

$$H(x, y) = \int_z o(x, y; z) \otimes h(x, y; z) dz, \quad (3)$$

where $h(x, y; z)$ is described as follows:

$$h(x, y; z) = \exp \left[\frac{ik}{2z} (x^2 + y^2) \right]. \quad (4)$$

By applying optical backpropagation to the complex hologram $H(x, y)$, object intensity distributions at a desired z position can be obtained as follows:

$$o(x, y; z_r) = H(x, y) \otimes h(x, y; -z_r), \quad (5)$$

where z_r is the reconstruction distance. The effect of binarization is discussed in Section 4.1.

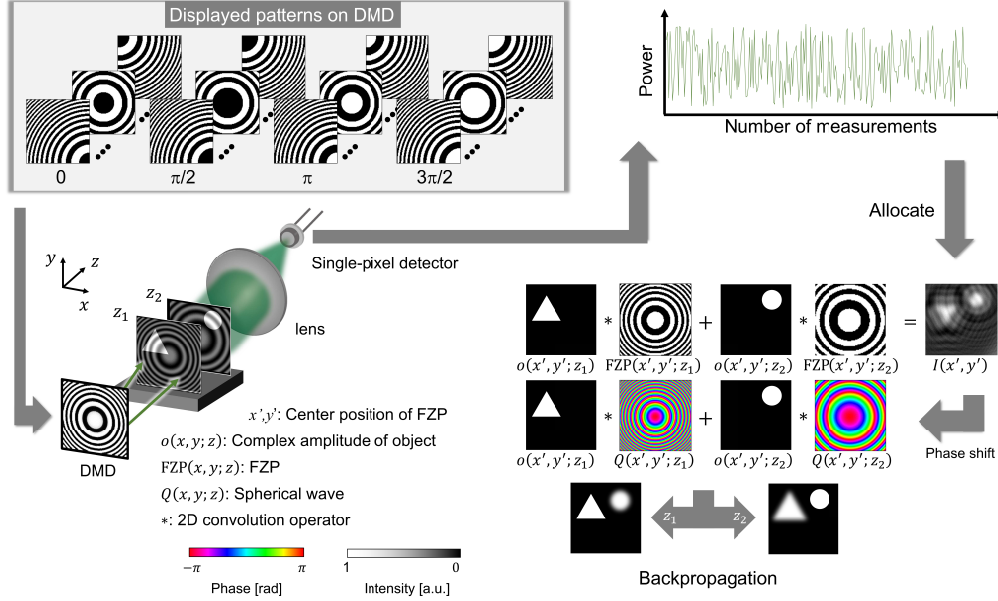


Fig. 1. Schematic of COSH with a DMD.

3. Experiment

3.1. Moving 2D object

A proof-of-principle experiment is performed. The schematic diagram of the optical setup is shown in Fig. 2. A solid-state laser with a wavelength of 532 nm (Oxxius OXX-532-50-COL-SLM) is used as light source. The collimated light illuminates a DMD (Vialux V-7001, 1024 × 768 micromirrors, 13.67 μm micromirror pitch), that has a refresh rate of 22727 Hz. The focal length of the FZPs is set to 74 mm to satisfy the sampling requirements [24]. Because the number of pixels of the recorded hologram is set to 128 × 128 and the spatially divided phase-shifting method [24] is used, the number of patterns uploaded to the DMD is 16384, which satisfies the memory requirement of the DMD. The principle of the spatially divided phase-shifting method is shown in Appendix A. The frame rate of the complex hologram is 1.387 Hz with this experimental conditions. The light sampling patterns generated by the DMD are projected onto an object plane with a 4- f optical setup. The amplitude mask of the logo of Universitat Jaume I (UJI) mounted on a linear translation stage is used as a moving object as shown in Fig. 2(b) and (c). The light transmitted by the object is focused by a lens and detected by a single-pixel detector (DET10A/M).

The setup shown in Fig. 2 allows us to record incoherent holograms of the moving object. The recorded holograms are shown in Fig. 3(a) and Visualization 1. Reconstructed intensity distributions from the holograms are shown in Fig. 3(b) and Visualization 2. Reconstructed intensity distributions from the hologram plane to the object plane can be seen in Visualization 3.

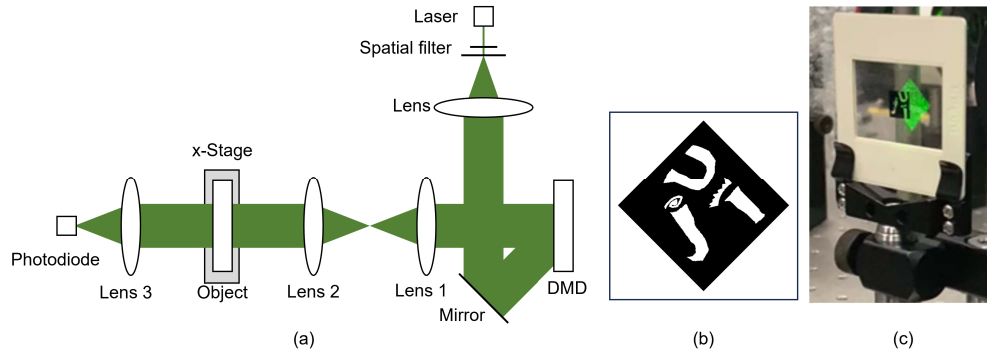


Fig. 2. (a) Schematic of the experimental setup, and (b) transmittance of the object, and (c) a photo of the object used in the experiments, on a linear translation stage.

Note that [Visualization 1](#) and 2 play at 5 times the speed. The flashing in [Visualization 1](#) is caused by laser temporal fluctuation. This flicking noise can be removed through the phase-shifting process because this intensity fluctuation affects only the bias intensity of holograms. In addition, the reconstructed intensity is in a different plane from that of the hologram; therefore, the effect of the fluctuated hologram can be reduced at the object plane according to the Fresnel backpropagation. The velocity of the moving object is set to 2.4 mm/s. The experimental results of [Fig. 3](#) indicate that the proposed method can record dynamic events with a frame rate of 1.387 Hz.

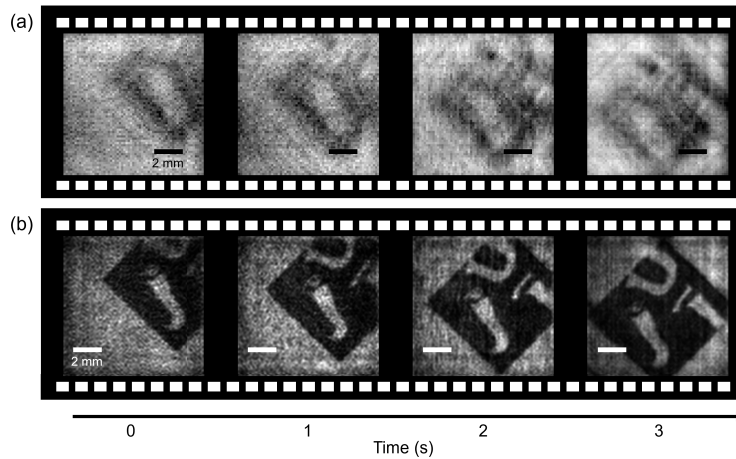


Fig. 3. (a) Obtained incoherent holograms and (b) reconstructed intensity distributions.

3.2. 3D object

We also experimented with a 3D object as shown in [Fig. 4\(a\)](#). The experimental conditions are the same as that of [Section 3.1](#). The amplitude mask of the logo of UJI and a USAF test chart mounted to fixed stages are used as a 3D target. The maximum distance between the two flat objects to simulate a 3D object for which reconstruction is feasible is determined by the depth of field (DoF). The DoF with this condition is 2.96 mm. The distance between each object is set to 7.1 mm. The reconstructed intensity distributions at each object plane are shown in [Fig. 4\(b\)](#) and (c), for the UJI logo and the USAF test, respectively. Red arrows indicate the objects at the focus

positions. Reconstructed intensity distributions from the hologram plane to the object plane can be seen in [Visualization 4](#). The results of Fig. 4(b) and (c) indicate that the proposed method can change the focus position using computational diffraction calculations.

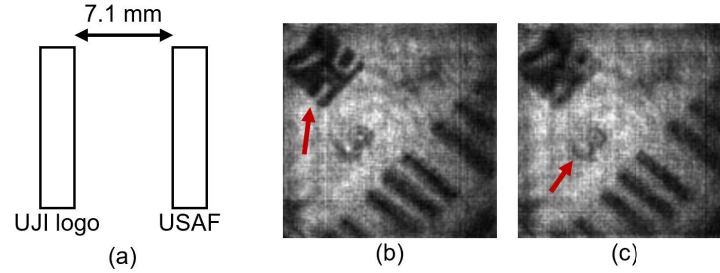


Fig. 4. (a) Positions of the UJI logo and USAF test to configure a 3D object. Reconstructed intensity distributions at (b) UJI logo plane and at (c) USAF test target plane.

A moving 3D object is also observed by the proposed method. The position of two flat objects located at two different axial planes is shown in Fig. 5(a). The experimental conditions are also the same as that of Section 3.1. The transparent amplitude mask of the logo of UJI mounted to a translation stage and a USAF test chart mounted to fixed stages is used as a 3D target. The distance between each object is set to 3.3 mm. The reconstructed intensity distributions at the USAF test chart plane are shown in Fig. 5(b) and [Visualization 5](#). Reconstructed intensity distributions from the USAF test target to the UJI plane can be seen in [Visualization 6](#). Note that the diffraction effect is unclear in [Visualization 6](#) because the distance between each object is almost the depth of field. The experimental results indicate that the proposed method can visualize dynamic 3D events.

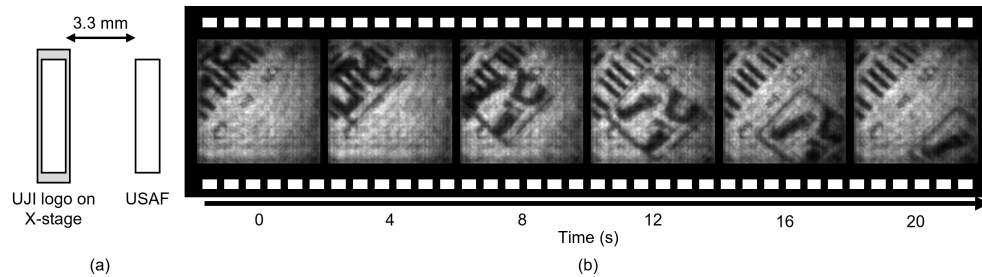


Fig. 5. (a) Relationship between each object and (b) reconstructed intensity distributions at USAF test target plane.

3.3. Imaging through scattering media under microscopy

Due to the advantage of COSH using a single pixel detector compared to FINCH using a 2D image sensor, the proposed method can be applied to imaging through scattering media. Particularly, imaging through scattering media under microscopy is required for biomedical applications. So we verified the applicability of COSH with a microscope. A microscope based on COSH is built as shown in Fig. 6(a). The wavelength of the light source and the DMD model are the same as in Section 3.1. Displayed patterns are 6 times magnified to use the full area of the DMD. The magnification and the numerical aperture of the objective lenses are 20 and 0.42, respectively. The diffraction limit of Abbe's criteria in this condition is $0.63 \mu\text{m}$. At the object plane, the pixel pitch of the DMD is $0.68 \mu\text{m}$. Due to the 6 times binning of illumination patterns, the resolution

of the FZPs at the object plane is $4.1\ \mu\text{m}$. An USAF test chart is used as object. An intact skull is used as scattering media as shown in Fig. 6(b). The intact skull shown in Fig. 6(b) is superimposed on the USAF test chart on a linear translation stage as shown in Fig. 6(c). Because the object and the skull are simultaneously shifted by the translation stage, the dynamic scattering condition can be realized. The thickness of the mouse skull is approximately $2\ \mu\text{m}$. The light from the object is relayed on detector planes with a $4f$ optical setup. An image sensor (Thorlabs CS235MU) is used as a comparison.

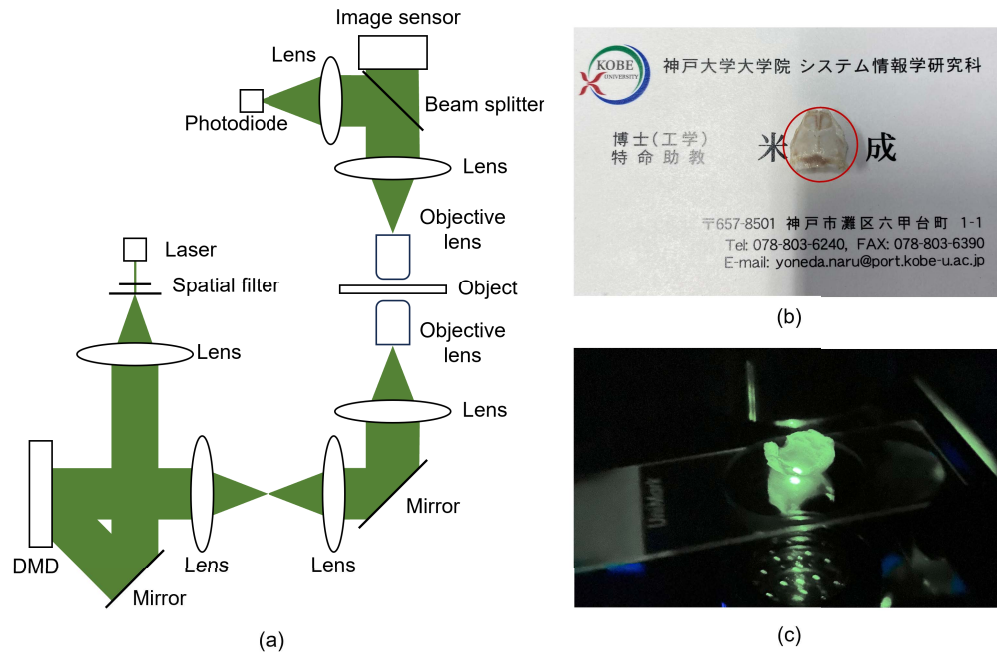


Fig. 6. (a) Schematic of the single-pixel holographic microscope, (b) photo of a mouse skull onto a business card of the first author (in Japanese), and (c) photo of the mouse skull in the experimental setup, located between objective lenses.

The experimental result obtained by the image sensor is shown in Fig. 7(a). Due to the scattering caused by the mouse skull, the USAF test chart cannot be observed by the image sensor. On the other hand, the proposed method can visualize the USAF test target as shown in Fig. 7(b) and Visualization 7. Note that the reconstructed intensity distributions have fluctuations caused by the non-uniform illumination of the DMD and loss of detected intensity caused by the limited detector size. The fluctuation can be overcome by optimizing the parameters of the optical elements and the detector. These experimental results indicate that the proposed method can measure dynamic events through dynamic scattering media.

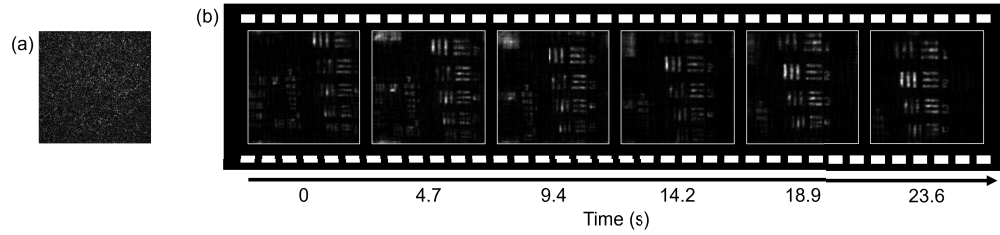


Fig. 7. (a) Image of an USAF target under the scattering media obtained by the image sensor and (b) reconstructed intensity distributions provided by the proposed method for a moving target.

4. Discussions

4.1. Effect of binarization

To use the DMD with the maximum refresh rate, the binary operation mode of the DMD must be selected. Therefore, it is necessary to binarize the illumination patterns. In this Section, the effect of the binarization is numerically evaluated. Parameters of the simulated optical setup are the same as that in Section 3.1. An image of the target distribution is shown in Fig. 8(a). The quality of the reconstructed intensity distributions provided by different COSH systems [23–27] is compared. Specifically, motionless OSH (MOSH), spatially divided phase-shifting MOSH (SP-MOSH), interferenceless OSH (IOSH), and spatially divided phase-shifting IOSH (SP-IOSH) are used for the comparison. The optical setups of these COSH techniques are almost the same, but MOSH uses an LCOS-SLM and IOSH uses a DMD for illumination. In our simulation, MOSH and IOSH use the four-step phase-shifting method to remove unnecessary components. Note that MOSH and SP-MOSH use multi-level FZPs, and IOSH and SP-IOSH use binary FZPs.

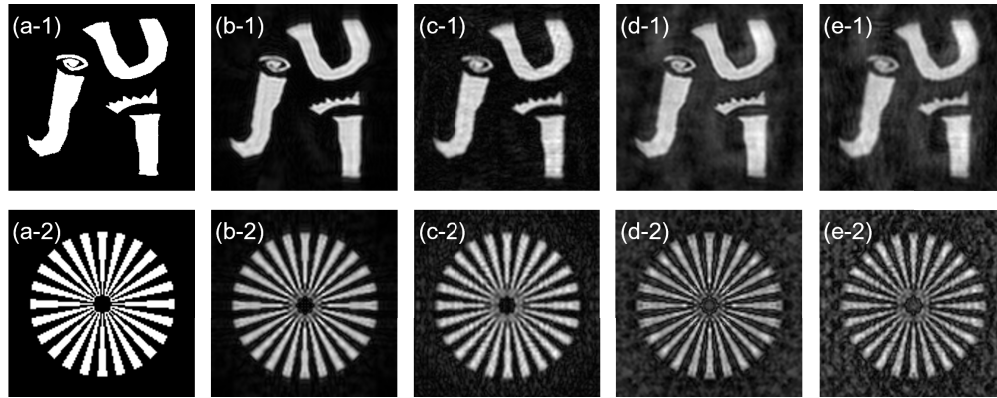


Fig. 8. (a) Target objects and reconstructed intensity images obtained by (b) conventional MOSH, (c) SP-MOSH, (d) IOSH, and (e) SP-IOSH.

The simulation results are shown in Figs. 8(b)–(e). In the cases of IOSH and SP-IOSH, there is background noise due to the binarization of the FZPs. The image quality of the reconstructed intensity distributions is quantitatively evaluated with the peak signal-to-noise ratio (PSNR).

The results of PSNRs are shown in Table 1. From the results in Fig. 8 and Table 1, we conclude that, although the target intensity distribution is reconstructed from holograms, image quality is good because it is possible to identify the shape and edges of the object. However, the contrast is worse when the illumination patterns are binarized. From the results of Siemens Star as shown in

Fig. 8(b-2)-(e-2), we find that the spatial resolution does not change even in the case of IOSH. If the cutoff frequency is defined as the contrast below 85%, the cutoff frequencies in the results of Fig. 8(b-2)-(e-2) are 27.6, 24.4, 27.6, and 25.2 cycles/mm, respectively. Simulation results indicate that the binarization induces the reduction of the image quality.

Table 1. Comparison of PSNR values for reconstructed images using the COSH techniques.

	MOSH	SP-MOSH	IOSH	SP-IOSH
UJI logo	21.9	20.5	16.2	15.7
Siemens Star	13.6	13.2	11.2	11.0

We compare the results provided by the different methods by evaluating the image quality, spatial resolution, and temporal resolution as shown in Table 2. In this comparison, we assumed that MOSH uses a liquid-crystal type SLM with a refresh rate of 60 Hz and IOSH uses a DMD with a refresh rate of 22 kHz. From the comparison, we conclude that although the image quality is not so high, SP-IOSH is the best selection for measuring dynamic events.

Table 2. Comparison of the PSNR in MOSH, SP-MOSH, IOSH, and SP-IOSH for 100×100 pixel image reconstruction.

Methods	Spatial resolution [cycles/mm]	Temporal resolution [Hz]	Image quality
MOSH	27.6	0.0015	high
SP-MOSH	24.4	0.006	moderate
IOSH	27.6	0.55	low
SP-IOSH	25.2	2.2	low

4.2. Effect of subsampling

To reduce the acquisition time, the number of measurements should be reduced. Recently, the random sparse subsampling technique has been proposed to reduce the number of measurements [29]. In this subsection, random sparse subsampling is applied to the proposed method. Simulation conditions are the same as that of Section 3.1. The illumination patterns are randomly selected according to Ref. [29]. The optimization problem is solved with a two-step iterative shrinkage/thresholding (TwIST) algorithm. Simulation results are shown in Fig. 9. The PSNRs of the images in Fig. 9 are shown in Table 3. From these results, we find that the target object can be reconstructed even when the sampling rate is 5 % although the image quality is not so high. In this condition, the proposed method can work with a frame rate of 26.9 Hz.

Table 3. Comparison of PSNRs with different subsampling rates.

Sampling rate [%]	80	60	40	20	5
MOSH	11.9	12.2	11.9	11.3	10.7
IOSH	10.6	10.9	10.9	10.5	10.1

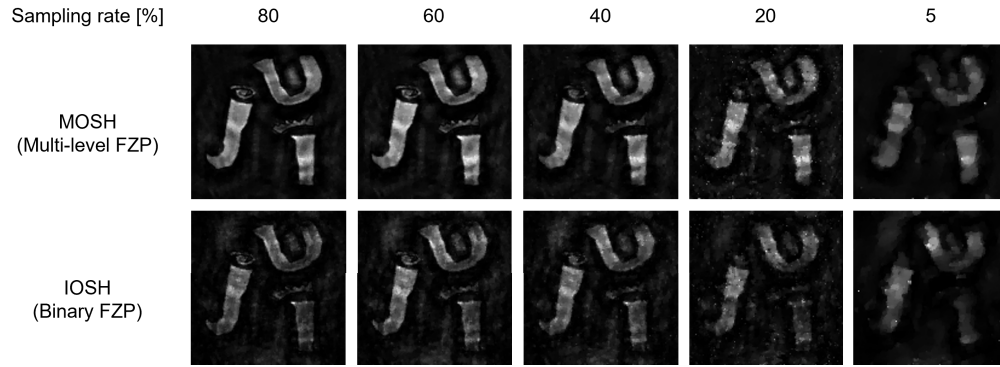


Fig. 9. Simulation results of random sparse sampling and compressive sensing.

5. Conclusions

In this paper, COSH for dynamic event measurements with a DMD is proposed. The feasibility of the proposed method is experimentally verified. The proposed method can measure 2D and 3D objects in static and dynamic situations. By applying the proposed method in a microscope

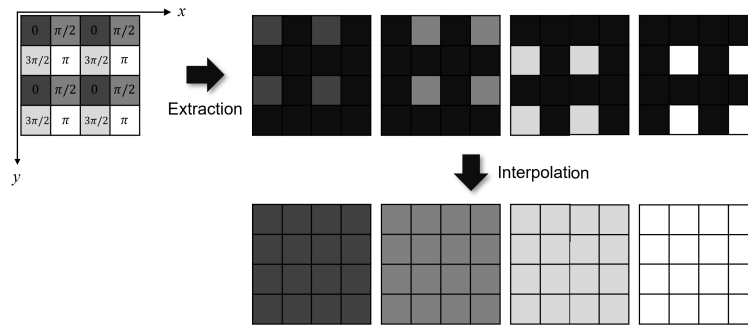


Fig. 10. Schematic diagram of the spatially divided phase-shifting method.

configuration, we have verified that it is possible to visualize a microscopic object (a USAF target) occluded by a scattering medium (a mouse skull). Although discrete objects were used for a 3D object in the paper, 3D objects with continuous depth variations are also measurable by the proposed method. In addition, by using random sparse sampling, we have proved through numerical simulations that an incoherent hologram with 128×128 pixel can be obtained with a frame rate of 27.7 Hz. Of course, the frame rate of the proposed method is slower than that of other methods for IDH based on 2D cameras such as FINCH, so FINCH is now a better choice for observing high-speed phenomena. However, if the observed targets are not moving so fast, the proposed method could be useful for multi-color imaging with non-visible light and imaging through scattering media or flame. In the near future, we plan to improve the quality of the images by using optimal binarization techniques for FZPs and deep learning-based reconstruction.

Appendix A

The schematic of the spatially divided phase-shifting method is shown in Fig. 10. Similar to parallel phase-shifting digital holography, each pixel in the obtained hologram has different phase-shift values. By changing the position and bias phase of FZP simultaneously in the

measurement process of COSH, the spatially divided phase-shifting hologram can be obtained. An obtained hologram can be described as follows:

$$I(x, y) = \begin{cases} \int_z o(x, y; z) \otimes \text{FZP}_0(x, y; z) dz, & (x \text{ and } y \text{ are odd}) \\ \int_z o(x, y; z) \otimes \text{FZP}_{\frac{\pi}{2}}(x, y; z) dz, & (x \text{ is odd and } y \text{ is even}) \\ \int_z o(x, y; z) \otimes \text{FZP}_{\pi}(x, y; z) dz, & (x \text{ and } y \text{ are even}) \\ \int_z o(x, y; z) \otimes \text{FZP}_{\frac{3\pi}{2}}(x, y; z) dz, & (x \text{ is even and } y \text{ is odd}) \end{cases} \quad (6)$$

By using interpolation, phase-shifted holograms can be obtained. A complex hologram described in Eq. (3) can be obtained through the phase-shifting technique.

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Disclosures. The authors declare no conflicts of interest.

Data availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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