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Abstract

We propose single-shot incoherent digital holography in which a single-path in-line configuration and phase-shifting interferometry are adopted. Space-division multiplexing and polarization states of the waves are utilized to implement parallel phase-shifting holography. A single-path setup in parallel phase-shifting is constructed to capture an incoherent hologram easily with a compact system. An instantaneous and three-dimensional (3D) object image is obtained without undesired diffraction waves using parallel phase-shifting. The validity of the proposed technique is experimentally demonstrated for both transparent and reflective objects.

Keywords: digital holography, holography, phase-shifting interferometry, incoherent 3D imaging, incoherent holography

(Some figures may appear in colour only in the online journal)

1. Introduction

Demand for multidimensional information such as three-dimensional (3D) space \cite{1, 2}, wavelengths \cite{3, 4}, and polarization state has been increasing more and more in recent years. Acquisition of 3D information is important particularly in the fields of life science \cite{1} and information science \cite{2}. To record a 3D position, shape, and image of an object, many types of methods such as dual focus-plane imaging \cite{1}, integral imaging with a lens array \cite{2}, scanning and nonlinear optics \cite{4}, coherent diffraction imaging \cite{5}, and holography \cite{6-10} have been actively researched. Although coherent diffraction imaging and holography can achieve high-resolution 3D motion-picture imaging of multiple objects simultaneously, a spatially coherent light source is required. Incoherent digital holography is a technique to record the complex amplitude distribution of fluorescent, natural light, or another spatially incoherent light, and to reconstruct a 3D image of a scene using a computer \cite{11-20}. Most incoherent digital holography systems adopt temporal phase-shifting interferometry. Phase-shifting interferometry \cite{21-23} can remove undesired diffraction images, zeroth-order diffraction waves, and conjugate images from an object wave, and has been applied not only to 3D image measurement but also to color imaging \cite{24-27}. Parallel phase-shifting digital holography \cite{28-33} is a single-shot phase-shifting technique using an in-line system, and single-shot incoherent 3D imaging is expected by the combination of incoherent digital holography.

In this paper we propose single-shot, single-path, in-line, and phase-shifting incoherent digital holography to achieve instantaneous 3D imaging of objects illuminated by natural light. The concept of the proposal is based on \cite{34}. Transmission- and reflection-type optical systems are designed and constructed for experimental demonstrations. We used light polarization to implement a single-path parallel phase-shifting incoherent digital holography system. Experimental results
show the simultaneous recording of four phase-shifted incoherent holograms with a single-shot exposure and 3D imaging of incoherent light from a single recorded image.

2. Parallel phase-shifting incoherent digital holography

The concept of the proposed digital holography is based on incoherent digital holography and parallel phase-shifting. Incoherent digital holography can be implemented with a single-path setup by using a spatial light modulator (SLM); this is called Fresnel incoherent correlation holography (FINCH) [14–17]. An SLM generates two waves that interfere with each other and form an incoherent hologram to reconstruct an object image. An implementation that uses a polarization-sensitive SLM was recently reported [18]. Reference [18] describes that all pixels in a polarization-sensitive SLM creates two waves by utilizing light polarization at the cost of half the light intensity. As a result, resolution degradation is avoided and the intensity ratio is easily changed by rotating the polarizer placed in front of the SLM, which is shown in figure 1. The parallel technique utilizes space-division multiplexing of multiple phase-shifted holograms to conduct single-shot phase-shifting interferometry. An array of glasses, wave plates, light-modulation elements, or polarizers is set in the path of the reference beam or interference light to obtain phase-shifted images with a single-shot exposure. By using the array, the phase of the reference wave is spatially distributed. By utilizing the polarization states of the object and reference waves, a polarization-imaging camera with a micro-polarizer array captures a hologram that contains the information of multiple phase-shifted interferograms. Figure 1 illustrates an implementation in parallel phase-shifting incoherent digital holography. This setup is composed by the combination of FINCH utilizing polarization [18] and parallel phase-shifting digital holography [28, 32]. Incoherent light illuminates an object and light diffracted by the object passes through a polarizer to be changed from random polarization into linear polarization in a diagonal direction. Then, a polarization-sensitive retarder such as an SLM displays a quadratic phase pattern to shift the phase of vertically polarized light, and generates two waves whose wavefronts are different from each other. A quarter wave plate changes the two waves into circularly polarized lights, as shown in figure 1(b), and generates different phase shifts against the polarization direction, which is based on polarization phase-shifting [32]. As a result, a polarization-imaging camera, described in figure 1, captures an image in which four intensity images are contained. By the combination of a quarter wave plate and a micro-polarizer array, the
information of four phase-shifted holograms with the phase shifts \(0, \pi/2, \pi,\) and \(3\pi/2\) is simultaneously recorded. Here, \(A_1(x, y)\) and \(A_2(x, y)\) are amplitude distributions of waves with and without the modulation by an SLM, respectively, and \(\phi(x, y)\) is a distribution of a phase difference between two wavefronts. A recorded hologram \(I(x, y)\) is expressed as follows:

\[
I(x, y) = \begin{cases} 
I(x, y; 0) & \text{when } (x, y) = (\text{odd, even}) \\
I(x, y; \pi/2) & \text{when } (x, y) = (\text{even, even}) \\
I(x, y; \pi) & \text{when } (x, y) = (\text{even, odd}) \\
I(x, y; 3\pi/2) & \text{when } (x, y) = (\text{odd, odd}) 
\end{cases}
\]

\[
= \begin{cases} 
|A_1(x, y)|^2 + |A_2(x, y)|^2 + 2A_1(x, y)A_2(x, y)\cos \phi(x, y) & \text{when } (x, y) = (\text{odd, even}), \\
|A_1(x, y)|^2 + |A_2(x, y)|^2 + 2A_1(x, y)A_2(x, y)\sin \phi(x, y) & \text{when } (x, y) = (\text{even, even}), \\
|A_1(x, y)|^2 + |A_2(x, y)|^2 - 2A_1(x, y)A_2(x, y)\cos \phi(x, y) & \text{when } (x, y) = (\text{even, odd}), \\
|A_1(x, y)|^2 + |A_2(x, y)|^2 - 2A_1(x, y)A_2(x, y)\sin \phi(x, y) & \text{when } (x, y) = (\text{odd, odd}). 
\end{cases}
\]

Figure 2 expresses an image-reconstruction procedure. Based on parallel phase-shifting [28], multiple phase-shifted holograms are numerically generated from a recorded hologram \(I(x, y)\) by de-mosaicing and interpolation procedures in a computer. In the de-mosaicing procedure, pixels are separately extracted with respect to the information of each phase-shifted hologram. Then, vacant pixels of each phase-shifted hologram are interpolated using neighboring pixels. Linear or another interpolation can be applied to generate multiple phase-shifted holograms from a recorded image. Here, we use the linear interpolation to conduct experimental demonstrations. With \(\Delta x\) and \(\Delta y\) as the pixel pitches, four phase-shifted holograms are numerically generated as follows:
Thus, multiple phase-shifted holograms required for phase-shifting interferometry, and \( I(x, y:0), I(x, y: π/2), I(x, y: π), \) and \( I(x, y: 3π/2) \) are numerically generated. Here, \( i = (-1)^{1/2} \) is an imaginary unit, and a complex amplitude distribution of incoherent light on the image sensor plane, \( A_i(x, y) \exp \{i\phi(x, y)\} \), is reconstructed by phase-shifting interferometry:
Thus, a complex amplitude distribution of an object wave on the image sensor plane is retrieved. Then, the complex amplitude distribution of the object wave at an arbitrary depth is obtained by applying diffraction calculations on the image sensor plane. As a result, a 3D image of an object illuminated by natural light is reconstructed by calculating diffraction integrals such as when using the angular spectrum method. A central wavelength is put into the formula of diffraction integrals to calculate numerical propagations. In parallel phase-shifting, several types of image-reconstruction algorithms have been proposed, and one can choose freely among them according to one’s purpose. In the proposed incoherent digital holography system, less wavelength dependency of the quarter wave plate is important to conduct parallel phase-shifting accurately when recording a temporally incoherent hologram. This is because object and reference waves are changed into not circularly but elliptically polarized waves for temporally incoherent light if the wave plate has a severe wavelength dependency. The intensities of object and reference waves differ greatly between the four holograms if these waves are elliptically polarized. Thus, phase-shifting interferometry does not work correctly and residual undesired diffraction waves slightly superimpose on an object image. Therefore, a broadband quarter wave plate should be prepared to record the four phase-shifted holograms and to conduct phase-shifting interferometry.

3. Experiments

Both transmission- and reflection-type optical systems for the proposed technique were constructed, and validity was experimentally investigated. Figure 3 illustrates a schematic of the constructed transmission-type system. A white light LED, whose light intensity was 20 lumen and diameter was 20 mm, was used as an incoherent light source, and a mask of the character ‘1’ was set as an object. The width of the character was 0.1 mm. Light intensity of the object-illumination wave after passing a 1-mm aperture was roughly estimated as 0.05 lumen. An incoherent hologram of the character was recorded by the proposed system. A lens whose focal length was 300 mm was used to collect incoherent light. The transmission axis of the polarizer was set as 45 degrees direction against the horizontal axis. An interference filter designed by SIGMAKOKI CO. Ltd was inserted as a bandpass filter and used to improve the visibility of the recorded hologram. The center wavelength of the transmission-wavelength band and the wavelength bandwidth of the filter were

\[
A_1(x, y) \exp \{i \phi(x, y)\} = \frac{I(x, y; 0) - I(x, y; \pi) + i \left\{ I(x, y; \frac{\pi}{2}) - I(x, y; \frac{3\pi}{2}) \right\}}{4A_2(x, y)}.
\]
The fast axis of the quarter wave plate was set as 45 degrees against the horizontal axis of the SLM. A polarization-imaging image sensor PolarCam, made by 4D Technology, with a number of pixels, pitch of pixels, and dynamic range of 640(H) × 460(V), 7.4 μm, and 8 bits, respectively, was used to record holograms. The polarization-imaging sensor worked in the whole visible wavelength range. A LCOS-SLM X10468 made by Hamamatsu Photonics K.K. was used as a polarization-sensitive SLM. The number of pixels and pixel pitch of the SLM were 800(H) × 600(V) and 20 μm, respectively. The SLM generates two waves, whose polarization directions are orthogonal with each other, and shifts the phase of one of the two waves. A quadratic phase pattern is displayed on the SLM to shift the phase of the wave.

In our experimental demonstration, the incoherent light wave on the image sensor plane was retrieved and the object image obtained with a single incoherent hologram by the
proposed technique. For comparison, we obtained a reconstructed image from an incoherent hologram and without phase-shifting. Figure 4 represents the experimental results. The information of four phase-shifted holograms was simultaneously recorded in an incoherent hologram by using space-division multiplexing of phase-shifted holograms, and therefore, a complex amplitude distribution of an incoherent hologram is extracted by applying phase-shifting interferometry. With the retrieved amplitude and phase images seen in figures 4(c) and (d), the focused object image was successfully reconstructed. As shown in figures 4(b) and (e), the proposed technique has the ability for clear incoherent 3D imaging without undesired diffraction waves. Speckle noise was not seen because the mask was categorized as a smooth object. Thus, single-shot 3D imaging of an incoherent object with a 0.1 mm width was experimentally demonstrated.

We have conducted further experiments for a reflective object. Figure 5 shows the schematic of the constructed reflection-type optical system in the proposed technique. The head of a miniature white-colored duck model was set as the reflective object, and its incoherent hologram was captured by the system described above. The light generated by the white light LED was collected by a lens to obtain an incoherent hologram by the image sensor. This was because most object-illumination light is scattered by an object with a rough surface, and only a low light intensity can be detected by an image sensor. Exposure time was 1 s and the light signal was digitally amplified in the sensor to record a hologram of weak light. Even where we set the conditions described above, most of the pixel values of the interference term \(2A_1(x, y)A_2(x, y)\cos \phi(x, y)\) was from \(-10\) and 10 for an 8-bit image sensor. Figure 6 gives the experimental results. As shown in figure 6, digital refocusing was successfully done, and 3D imaging of the duck was demonstrated with a single incoherent hologram. Image quality degradation was due to the detection of only low light intensity and the low signal-to-noise ratio of the recorded image. Speckle noise was caused by small pixel values of the interference term, and then object wave information was lost. Furthermore, noise such as dark currents had high pixel values because the light signal was digitally amplified in the sensor to record a hologram of weak light. Therefore, interference between the retrieved object wave and the amplified noises occurred. For improving image quality, it is valid to record an incoherent hologram with high visibility and high intensity. These results mean that it is possible to conduct single-shot and lensless 3D imaging of a reflective object with an in-line and common-path configuration and temporally and spatially incoherent light.

4. Conclusion

We have proposed single-shot, in-line, and phase-shifting incoherent digital holography. An implementation was proposed and described, and its optical system was constructed. Single-shot 3D imaging of an object illuminated by incoherent light was experimentally demonstrated. Experimental results showed that the unwanted images, zeroth-order diffraction wave, and conjugated image, were clearly removed while severe image quality degradation was seen in the image reconstructed by the diffraction integral without phase-shifting interferometry. This paper clarified that single-shot in-line phase-shifting interferometry can be applied to incoherent digital holography with a single-path setup. By applying parallel phase-shifting to incoherent digital holography, single-shot 3D imaging of incoherent light is achieved without any imaging lenses in principle. Single-path in-line configuration eases the requirement to adjust the optical-path difference between two waves. On the other hand, we must pay more attention to the sampling theorem due to space-division multiplexing of multiple phase-shifted holograms. High light intensity is required in comparison to sequential phase-shifting techniques to obtain a 3D image of the object with high quality from a single hologram. This time the speckle noise was seen for a reflective object, and it was considered that the main reasons for this was the loss of object wave information due to low light intensity of the interference term and interference between the object wave and noise components during reconstruction. Sufficient light intensity to obtain a fringe image with a high dynamic range in an image sensor is essential to reconstruct a clear speckle-less image, as seen in [14]. The combinations with fluorescent microscopy and a holographic motion-picture camera with natural light are considered as prospective applications of the proposed technique. The proposed technique can obtain an incoherent hologram of light with a short coherence length, and will contribute to life and information sciences as a lensless 3D motion-picture recording method of natural light, such as sunlight and light derived from a variety of emission phenomena.

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