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Investigation of super-resolution processing algorithm by target light-intensity search in digital holography

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ABSTRACT

Digital holography is expected to be useful in the analysis of moving three-dimensional (3D) image measurement. In this technique, a two-dimensional interference fringe recorded using a 3D image is captured with an image sensor, and the 3D image is reproduced on a computer. To obtain the reproduced 3D images with high spatial resolution, a high-performance image sensor is required, which increases the system cost. We propose an algorithm for super-resolution processing in digital holography that does not require a high-performance image sensor. The proposed algorithm wherein 3D images are considered as the aggregation of object points improves spatial resolution by performing a light-intensity search of the reproduced image and the object points.

1. Introduction

The research and development of a three-dimensional (3D) measurement technique is receiving increasing attention. Generally, one- or two-dimensional sensor scans are required to obtain 3D information. This method requires multiple measurements to measure a 3D object; this involves a considerable amount of time. Consequently, measuring fast-moving 3D objects is difficult. Digital holography [1,2] has been proposed as an effective method to measure moving 3D objects [3–5].

In digital holography, the light reflected or transmitted from a 3D object interferes with a reference light, and the interference pattern is captured by an image sensor in a single shot. Note that an image sensor scan is not required. In this method, the interference fringe is called a hologram and the light reflected or transmitted from the 3D object is referred to as object light. A hologram can store both amplitude and phase information of the light from the 3D objects and the 3D image is reproduced on a computer using numerical diffraction calculation. Thus, fast-moving 3D objects can be measured. Digital holography is expected to be applied to the analysis technology for moving 3D objects.

However, with digital holography image reproduction, false detection of 3D objects can occur and image quality can deteriorate due to the diffraction phe-nomenon. The 3D object is considered an aggregation of object points. The hologram and the reproduced image generated from a single object point are shown in Fig. 1.

The intensity profile of the central row of the reproduced image (Fig. 1(c)) is shown in Fig. 2. Table 1 lists the calculation conditions.

In Fig. 2, the object point is originally located at the triangle mark; however, the intensity profile is widened due to diffraction. Therefore, detecting the position of the object point from the intensity profile is difficult. It is difficult to discriminate adjacent object points due to interference between the light diffracted from the object points. In addition, the interference intensity of the diffraction light may be stronger than the intensity of the object point. If object point positions are detected using only the intensity of the reproduced image, a significant number of false detections will occur.

In Fig. 3, we show the reproduced image of two object points at a distance of 100 μm. The calculation conditions are listed in Table 1.

In the right panel of Fig. 3, the blue triangles indicate the actual positions of the two object points. However, the red triangle shows the maximum intensity of light. The maximum intensity of light does not coincide with the positions of the two objects points indicated by the blue triangles. In other words, when two points are spaced adjacently, false detection occurs when only the intensity level of the reproduced image is used. Generally, the resolution of the reproduced image is determined by $\delta = \lambda/2NA$, where λ and NA denote wavelength and numerical aperture, respectively. Therefore, if we capture a larger hologram, higher resolution images can be obtained. However, a larger and more expensive image sensor is required to capture a larger hologram. In addition, a larger image sensor would require a different optical system. Several super-resolution algorithms that record multi-

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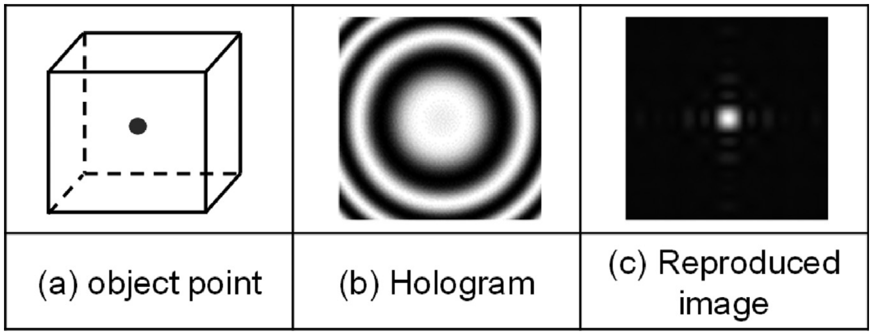

Fig. 1. Hologram and reproduced image when an object point is recorded.

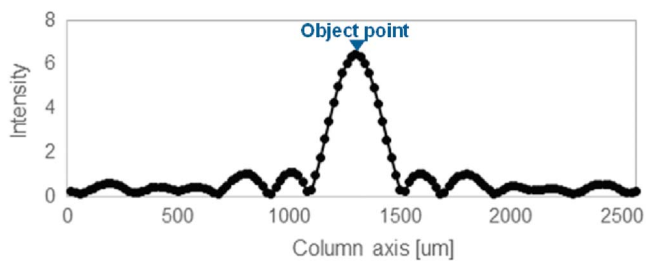

Fig. 2. Intensity profile of the central row in Fig. 1(c).

Table 1
Calculation conditions.

Pixel pitch	20 µm
Hologram size	128×128 pixels
Wave length	520 nm
Distance from object point to hologram	1.0 m

ple holograms and do not require changing the image sensor have been proposed [6–11]. However, it takes time to record holograms; thus, these algorithms are not applicable to real-time measurements. The goal of this paper is to develop a calculation algorithm that improves the detection accuracy of object points without changing the performance level of the image sensor and without capturing multiple holograms. The proposed algorithm in which objects are considered the aggregation of object points improves the spatial resolution by performing a light-intensity search of the reproduced image and object points.

The remainder of this paper is organized as follows. The proposed method is described in Section 2. In Section 3, we demonstrate that the proposed method can improve the resolution of reproduced images in a numerical simulation. Conclusions are presented in Section 4.

2. Proposed method to improve resolution

Reproduced images from holograms can be considered as the superposition of a light wave from each object point because objects are regarded as the aggregation of object points. As shown around the center position in Fig. 2, high intensities are observed in the absence of object points due to the diffraction light from the object point, However, the influence of the diffraction light is significantly reduced at a certain distance from the object points.

Fig. 4(a) shows the original object whose object points are distributed in a cross pattern where the space between the object points is 260 µm. Fig. 4(b) shows the reproduced image obtained from the hologram generated from Fig. 4(a). When the positions of the object points are detected directly from the reproduced image, a “direct method” uses local high intensities that are greater than a given threshold as detected object points. Unfortunately, the direct method cannot provide accurate object point positions. Fig. 4(c) shows the intensity contours and local high intensities of Fig. 4(b). Comparing Fig. 4(a) with Fig. 4(c), it is evident that local high intensities are observed in the absence of the actual object points, which leads to false detection of the object points.

In addition, the number of detected object points is less than that of the original 12 object points shown in Fig. 4(a). In summary, when object points are positioned densely, it is difficult to detect actual object points using only the intensity of a reproduced image due to the interference of diffracted light from each object point.

With reference to Fig. 5, we investigate the interference of points P1 and P2 (Fig. 4(a)). Fig. 5(a) shows the two original object points, and Figs. 5(b) and (c) show the reproduced image, the intensity contour, and the high local intensity. Fig. 5(d) shows the intensity profile of the central row in the reproduced image. As shown in Fig. 5(d), the intensity around the central region indicated by the dashed green lines becomes high due to the interference of the diffraction light of the two object points.

However, intensities become weak in regions that are distant from the two object points. Therefore, the region in the right side of the local high intensity of object point P1 is strongly affected by the diffraction

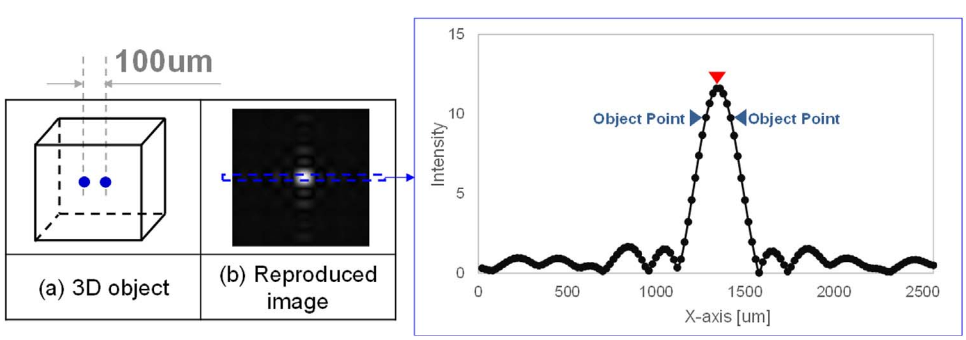

Fig. 3. Reproduced image of two object points (distance between points is 100 µm). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)