# Resolution enhancement of incoherent digital holography using the super resolution image reconstruction technique

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**Abstract:** The reconstruction process of incoherent digital holography, which can overcome the resolution limitation imposed by the imaging device, is proposed based on the super resolution image reconstruction technique.
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## 1. Introduction

The basic principle of the holographic imaging, which requires the coherent light source, prevents its widespread use in practical applications. Hence there have been many efforts to record the hologram under the condition of the incoherent illumination since the early years of the history of the holographic imaging [1]. In recent years, there have been several successful reports about this issue with various different approaches [2-4]. One of the most attractive approaches is the Fresnel incoherent correlation holography (FINCH) which uses the self-coherency of the point source by using the spatial light modulator (SLM) which can operate as the combination of a concave mirror and a simple flat mirror [4]. Recently, we have presented the incoherent digital holography (IDH) scheme that can be applied to the compensation of the aberration in the telescope imaging or other applications using the guide star hologram [5, 6]. Though the spatial incoherency between the point sources washes out the interference pattern as the number of the point source increases, the adoption of the digital imaging devices such as the charge coupled device (CCD) makes it possible to obtain the complex hologram by the phase shifting method. However, because the resolution of the available CCD is not sufficiently high yet, the imaging characteristic of IDH is usually restricted by the specifications of the adopted CCD.

In this paper, we present the method to enhance the resolution of the image reconstructed through the IDH using the super resolution (SR) image reconstruction technique. SR, which is developed by the signal processing society, is a technique used for overcoming the resolution restriction imposed by the adopted imaging device. SR can achieve the resolution enhancement using the multiple images recorded by the same imaging device. Because the IDH also suffers from the low resolution of CCD, the SR technique also can be applied to enhance the resolution of the reconstructed image obtained by IDH.

## 2. Principle

The essential configuration of IDH is illustrated in Fig. 1. The entire setup is based on the modified Michelson interferometer. The beam splitter separates the spherical beam emanated from each point source at the object plane into two different paths. The curvatures of the separated spherical waves are varied by the different focal lengths of the concave (or convex) mirrors located in each path. The two spherical waves are superposed at the CCD plane creating the Fresnel-zone-like interference pattern. Because each point source has the spatial incoherency, the interference pattern washes out as the number of the point sources increases. Hence, the single image recording is not appropriate for the recording of the extended object. Instead, we adopt the phase-shifting process to extract the integral of the complex cross term. It can be easily implemented by addressing the piezo-induced shift to one of the mirrors.

The resolution limitation imposed by the performance of the CCD can be relieved by the SR technique. The SR enhances the resolution of the digital image by collecting the information from multiple images of the same scene [7]. Each image is assumed to have the lateral shift or warping in the sup-pixel scale. If we let the intended high resolution image as $\mathbf{x}$, each $k^{th}$ low resolution image can be represented as $\mathbf{y}_k = \mathbf{D}\mathbf{B}_k\mathbf{M}_k\mathbf{x}+\mathbf{n}_k$ where $\mathbf{D}$ is a subsampling matrix, $\mathbf{B}_k$ a blur matrix, $\mathbf{M}_k$ a warp matrix, $\mathbf{n}_k$ a noise vector. The first step of the SR is to estimate the shift or warping of the low resolution image in the intended high resolution grid. Then a proper interpolation is applied to the multiple images to reconstruct the high resolution image using the shift or warping information. The practical application also usually requires the noise removal. Figure 2 shows the usual process of the SR technique.

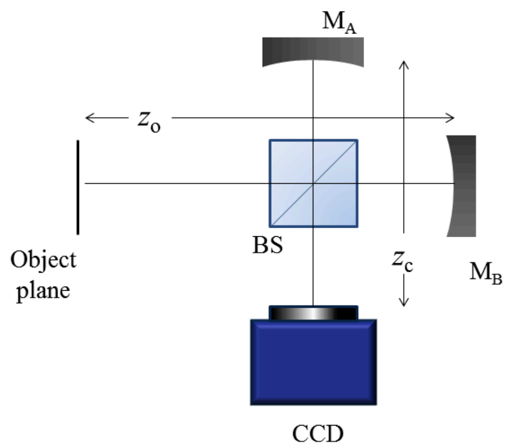


**Fig. 1**. Configuration for recording the hologram via IDH process. $M_A$ and $M_B$: Concave or convex mirrors. BS: Beam splitter.

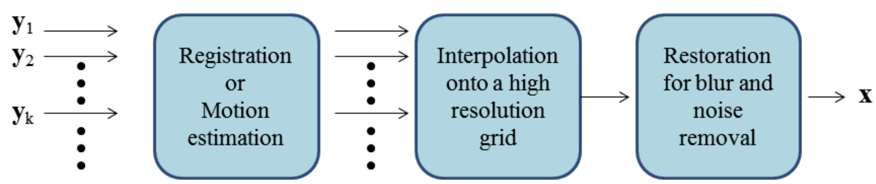


**Fig. 2**. The process of the SR technique to enhance the resolution from the multiple low resolution images

## 3. Results

To show the feasibility of our scheme, we have computationally acquired the hologram of the object shown in Fig. 3(a), which is the portion of the USAF 1951 resolution target, following the process illustrated in Fig. 1. In the calculation, the focal lengths of $M_A$ and $M_B$ were 3000 mm and 1000 mm respectively. The distance from the object to the mirror ($z_o$) was 3010 mm and the distance from the mirror to CCD ($z_c$) was 1000 mm. We have assumed the use of the wavelength of 600 nm by the filtering. The CCD has the 64 by 64 pixels and the pixel pitch was set to 80 μm. The 64 holograms were recorded with the sub-pixel shift of CCD and one of them is shown in Fig. 3(b). Figure 3(c) shows the reconstructed image from the hologram shown in Fig. 3(b), and it shows the severe resolution degradation due to the resolution limitation of the CCD. We applied the SR process to those 64 images to enhance the resolution by 8 times higher and the resultant image is shown in Fig. 3(d). As we can see from Fig. 3(d), the resolution of the reconstructed image by IDH can be much improved by using the SR process.

## 4. Conclusion

We have shown the effect of resolution improvement by applying the SR process to the image reconstruction of IDH. The computational result shows that the SR process can successfully improve the resolution of the reconstructed image obtained by IDH overcoming the limitation imposed by the CCD. In the presentation, we will show more practical examples obtained by the real experiment. And we also expect that the scheme also can be applied to the IDH adaptive optics which can compensate the aberration.

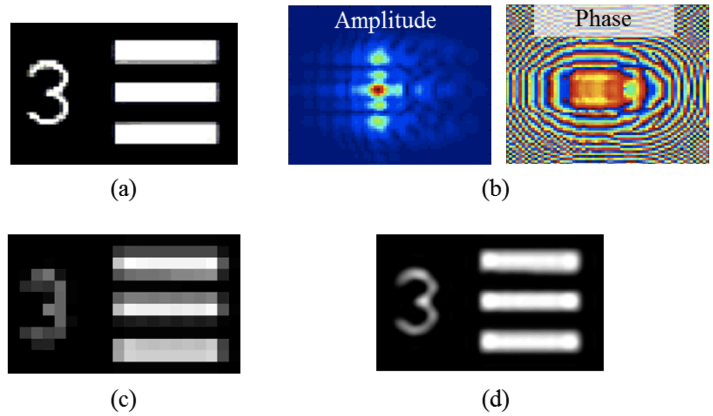


**Fig. 3**. (a) The object image. (b) The extracted complex hologram of one low resolution image. (c) The image reconstructed from the information of (b). (d) The high resolution image reconstructed from 64 low resolution images using the SR process.

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