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A simplified holography based superresolution system

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ABSTRACT

In this paper we are proposing a simple idea based on holography to achieve superresolution. The object is illuminated by three fibers which maintain the mutual coherence between the light waves. The object in-plane rotation along with fiber-based illumination is used to achieve superresolution. The object in a 4f optical system is illuminated by an on-axis fiber to make the central part of the object's spectrum to the pass through the limiting square-aperture placed at the Fourier plane and the corresponding hologram of the image is recorded at the image plane. The on-axis fiber is switched off and the two off axis fibers (one positioned on the vertical axis and the other positioned on diagonal) are switched on one by one for each orientation of the object position. Four orientations of object in-plane rotation are used differing in angle by 90°. This will allow the recording of eight holographic images in addition to the one recorded with on-axis fiber. The three fibers are at the vertices of a right angled isosceles triangle and are aligned toward the centre of the lens following the fiber plane to generate plane waves for object illumination. The nine holographic images are processed for construction of object's original spectrum, the inverse of which gives the super-resolved image of the original object. Mathematical modeling and simulations are reported.

1. Introduction

Superresolution imaging mainly addresses techniques used to resolve the object's contents beyond the classical limit. Optical resolution is mainly limited by the finite size of apertures in an imaging system and by the diffraction at the exit pupil of the imaging system. Finite size of CCD pixels and the separation between the pixels also limit the resolution called Geometric Superresolution. In the present work, we are assuming that the size of the CCD pixels is smaller than the size of the diffraction limited spot and that the separation between the CCD pixels is smaller than what is required to sample a given signal using Nyquist sampling. This implies that we are ignoring the resolution limit due to CCD pixels and are addressing only the optical aspect of the resolution limit. With the above mentioned characteristics the CCD may be regarded as an ideal imaging device.

To overcome the resolution limit due to diffraction, the imaging lens may be replaced with a lens of larger numerical aperture (NA) or the superresolution techniques may be employed with the lower NA lens to effectively improve its numerical aperture. Numerical aperture of an objective lens can be increased by using tilted beam illumination by employing either the vertical cavity surface emitting array laser, or an array of lenses or diffraction grating elements [1–5]. Using these techniques, the higher order spatial frequencies of the target object are recovered and thus the optical resolution is enhanced. Structured illumination in the form of projected fringes on the target object for enhanced resolution has also been reported [6,7]. To obtain super-resolved images while keeping the three dimensional aspect of the object intact, holography coupled super resolution techniques have been reported in [8–11]. These techniques are also named as digital holographic microscopy.

The structured illumination using an array of fibers is one of the recent techniques reported in [12] for the recovery of higher spatial frequencies of the object based on holographic superresolution. In this technique an array of fibers is used to illuminate the object from different directions and different portions of the object's spectrum are passed through the passband of the imaging system and the holographic images are recorded corresponding to different portions of the object's spectrum. The recorded holographic images are processed using an algorithm in which images are Fourier transformed and desired portion of the object's spectra is filtered and combined to synthesize the overall spectrum of the object. The synthesized object is then recovered by inverse Fourier transforming the synthesized spectrum. The main drawback with the technique in [12] is that it involves an array of large number of fibers for the synthesis of the object. In the present work this problem has been addressed.

In the current work we present a technique in which an array of large number of fibers used in the previous work reported in [12] is replaced by a small number of fibers at the expense of

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object rotation. Three fibers are enough for three times super-resolution imaging when combined with object rotation. The three fibers are arranged on the vertices of a right-angled isosceles triangle and one fiber at a time is used to illuminate the object transparency placed at the object plane in a 4*f* system. During the object illumination, the object is rotated in steps of $\pi/2$, π and $3\pi/2$ with respect to its initial orientation and images corresponding to different portions of the object's spectrum obtained in each step are recorded at the image plane in the presence of a reference beam, thus recording the image holograms corresponding to the different parts of the object's spectrum. The holograms are processed computationally and desired portions of the object's spectrum are retrieved which are then combined to obtain synthesized spectrum and synthesized image which we may refer to as super-resolved image. In the next section we are outlining the description of our proposed scheme for super-resolution.

2. System description

The proposed technique is a super resolution technique based on holographic imaging. It involves recording of different images at the image plane in the presence of a reference beam mutually coherent with the object beams. The proposed experimental arrangement consists of a He–Ne laser coupled to a 1 by 4 coupler with equal intensity outputs from the four output fibers. One of the output fibers acts as a reference beam and illuminates the image plane. The proposed technique uses very simple illumination consisting of three fibers which emit mutually coherent beams. The fibers are arranged with their distal ends lying on a plane perpendicular to the optical axis of a 4*f* imaging system and are at the vertices of a right angled isosceles triangle. The fiber 1 is positioned at the optical axis of the imaging system and the fibers 2 and 3 are located at the other two vertices of the isosceles right-angled triangle. The scheme is shown in Fig. 1. The fibers in the equal sides of the isosceles triangle are separated by the size of the limiting square-aperture to allow the adjacent parts of the spectrum to pass through the limiting aperture without any overlapping and without any discontinuity when operated by one fiber at a time.

The limiting aperture is a square aperture centered on the optical axis and is placed at the Fourier transform plane of the 4*f* imaging system parallel to the object plane. We have deliberately set up the dimensions of this limiting aperture to make the imaging system a band-limited system. The aperture will allow only a small part of the object's original spectrum to pass through it and contributes as an image on the image plane due to the inverse Fourier transforming nature of lens 3. Lenses 1, 2 and 3 all have the same focal lengths equal to *f* and are positioned after the fiber plane in the given order. The distal ends of the three fibers forming an object illumination system act as three point sources placed at the front focal plane of lens1. Lens 1 generates three plane waves corresponding to the three fibers to illuminate the object. Only one fiber will be used at one time and fiber 1 can be used once during the whole experiment. When fiber 1 is in the ON state and fibers 2 and 3 are in the OFF state then the part of the object spectrum that will pass through the limiting aperture is the central portion of the object's spectrum equal in size to the limiting aperture of the imaging system and is marked by 1 in the object's assumed spectrum shown in Fig. 2(a). The spectral portion marked by 1 is the band pass spectrum of the object (under no rotation) when illuminated by fiber 1. Image corresponding to this portion of the spectrum will be recorded as the hologram in the presence of the reference beam.

When the object is illuminated by switching ON fiber 2, the portion of the object spectrum marked by 2 in Fig. 2(a) will then pass through the limiting aperture of the optical system (Fig. 1) and the corresponding image hologram will be recorded on the charged coupled device (CCD). In the next step, fiber 3 is switched ON and the object is illuminated. The portion of the object's spectrum marked by 3 in Fig. 2(a) will then pass through the limiting aperture of the optical system (Fig. 1) and the corresponding image hologram will be recorded. With fiber 1 image hologram corresponding to the on-axis portion of the object spectrum with dimensions equal to the limiting aperture of the optical system is recorded whereas with fibers 2 and 3 image holograms corresponding to the off-axis portion of the object spectrum (labeled by portions 2 and 3 in Fig. 2(a)) are recorded.

The object is now rotated counter-clockwise by $\pi/2$ so that the portion of the spectrum labeled by “a” in Fig. 2(a) takes the position of portion 2 and the portion labeled with “b” takes the position of portion 3. The rotated spectrum is shown in Fig. 2(b). The object after rotation is illuminated by fibers 2 and 3 one by one and the $\pi/2$ counter-clockwise rotated portion of spectrum labeled by “a” and “b”, respectively, passes through the limiting aperture of the optical system and contributes as images at the image plane where the holograms of these images corresponding to these rotated portions of the spectrum are recorded. The object

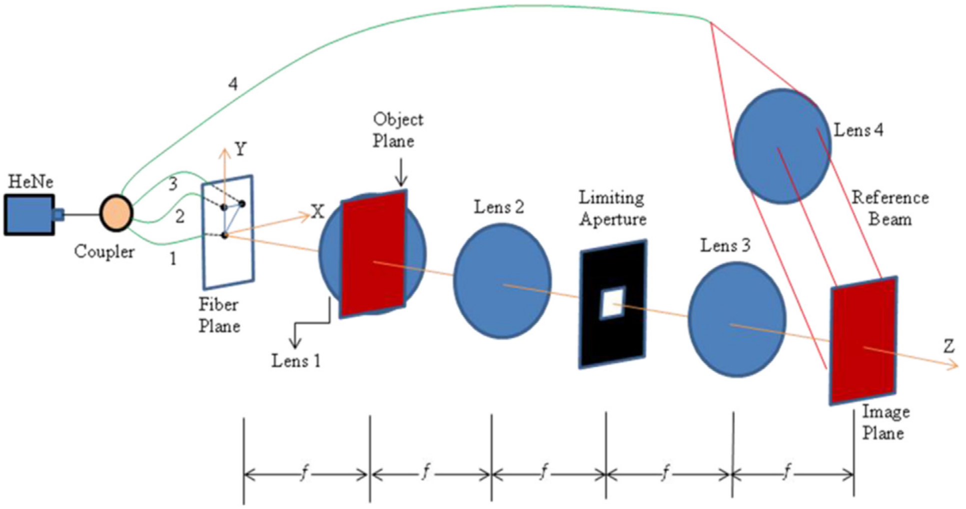

Fig. 1. Proposed experimental setup for holography based super-resolution using in-plane object rotation and simple fiber based illumination.