Synthetic aperture superresolution by speckle pattern projection

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Abstract: We propose a method for increasing the resolution of an aperture limited optical system by illuminating the input with a speckle pattern. The high resolution of the projected speckle pattern demodulates the high frequencies of the sample and permits its passage through the system aperture. A decoding provides the superresolved image. The speckle pattern can be generated in a simple manner in contrast with other structured light superresolution methods. The method is demonstrated in microscopy test images.

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1. Introduction

The classical resolution limit of an ideal imaging system is given by the diffraction spot size as $R=\lambda/(2\ NA)$, NA being the numerical aperture of the lens. This limit is given just by the wave nature of light, and it is considered as an unsurpassable bound for most practical cases. Nevertheless, the resolution limit is obtained under certain assumptions, such as source monochromaticity, unpolarized light, short time imaging, and so on. In fact, for many practical situations, additional degrees of freedom can be obtained by removing these assumptions and the classical resolution limit can be surpassed. This assertion is supported by the classical works of Toraldo di Francia and Luckosz [1-3], describing a system by the numbers of degrees of freedom it can transmit, instead of the space-bandwidth product. Later on, the signal-to-noise ratio (SNR) of the image was also included in the computation [4]. Thus, owing to the invariance of the information throughput of a system, the spatial resolution of a system can be enhanced, at the expense of other degrees of freedom [5]. As examples, the resolution in one axis can be enhanced by sacrificing the resolution of the orthogonal direction [2,6], or the two orthogonal polarizations can be used for doubling the resolution in the case of a polarization-independent object [7]. Methods based on extrapolation of the spectrum (Ref. [8], for instance) try to squeeze the SNR degree of freedom [5].

Obviously, the most appealing degree of freedom that can be used is the temporal one, owing to the high amount of available bandwidth for the cases in which the images are essentially static. Eventually, the maximum amount of information that can be multiplexed is given by the time-bandwidth product, related to the illumination source temporal spectrum. For a wavelength-independent object, several methods have been devised to encode the spatial resolution in different wavelengths, obtaining superresolution [9,10]. With a different approach, but also exploiting the temporal bandwidth of the source, it is possible to encode the spatial resolution in the coherence of the light [1112]. Both wavelength and coherence encoding methods are especially suitable for a 1 point spatial resolution channel, such as a single mode fiber. For the case of systems with a significant spatial resolution, the most widely studied methods are based on illuminating the object with tilted waves, such that the high spatial frequencies of the sample are down-converted into low spatial frequencies and thus can pass through a limited resolution system [13]. Passing high frequencies through the optical system is not enough, as the phase of the frequency bandpass must also be recovered. One way to surpass this problem is to record the phase by interferometry [14-16], although it requires a reference arm aside from the imaging system. Another widely used method employs moving gratings so that the different tilted beams coming from the grating are encoded in a phase that varies linearly with time [23,17]. A main problem of these systems is that they need a high resolution pattern (namely, a grating) to be projected onto the sample with high resolution—in general, this means a high quality system preceding the system to be enhanced.

In this paper we propose and demonstrate a superresolving system that uses as encoding mask a high resolution speckle pattern. The speckle pattern is obtained by free space propagation of the coherent light impinging on a diffuser. This way the illumination system can be extremely simple, in contrast to other methods that rely on grating projection, although high resolution imaging is attainable through a low NA lens.

2. Theoretical analysis

The system to be analyzed is just an imaging system with the object illuminated through a diffuser and with the capability for lateral shift of the object. The underlying concept can be summarized as follows: A high resolution mask is projected onto the object, producing a spread of the angular spectrum of the sample. This effect permits the high frequencies of the object to pass through the limited aperture lens. Later multiplication of the resulting image by a decoding mask recovers the high frequencies of the object.

The sketch of the system is shown in Fig. 1. The light coming from a temporally coherent source is sent to a diffuser. The light scattered by the diffuser generates a speckle pattern that becomes the illumination for the sample. The object is then imaged by means of an aperture limited lens into the image plane. The imaging lens NA is related to the angle that the lens subtends from the object plane as $NA = sin(\theta_L)$. θ_S is the angle subtended by the diffuser as seen from the object and will determine the speckle pattern's typical correlation length. Assuming a Lambertian diffuser, the effective size of the diffuser coincides with its physical size; that is, every point in the sample receives light from every point in the diffuser.

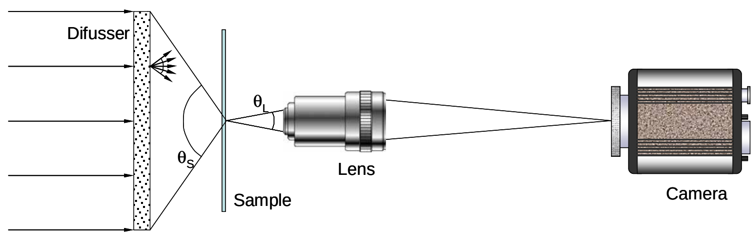

Fig. 1. Scheme of the experimental setup.

The operation principle involves the illumination of the sample with a set of high resolution speckle patterns, each one with a slight lateral displacement. The same speckle pattern, corrected with the system magnification, serves to decode each frame. The final reconstructed image is obtained by averaging the images obtained thusly. For simplicity, without loss of generality, we will assume a one dimensional process and unity magnification. Let *g(x)* be the input object, *s(x)* the speckle pattern on the sample plane, and *s'(x)* the decoding mask. The diffuser is laterally displaced with time synchronously with the camera (in practice it is simple to move the sample, as we will discuss later). We denote ξ the displacement of the diffuser at a certain instant, which coincides with the displacement of the speckle pattern projected onto the object. The imaging lens produces a low pass filtering, owing to diffraction, which can be modeled by the impulse response *h(x)*. Therefore, one single frame in the camera will be

$$o_\xi(x) = [g(x)s(x-\xi)] \otimes h(x) = \int [g(x')s(x'-\xi)] h(x-x')dx' , \quad (1)$$

where ⊗ denotes convolution. Then the image is multiplied by the decoding pattern, displaced by the same amount as the illumination pattern and added for all displacements. This yields the integrated image

$$o(x) = \int o_\xi(x)s'(x-\xi)d\xi = \int\int \{[g(x')s(x'-\xi)] h(x-x')\} s'(x-\xi)dx'\, d\xi . \quad (2)$$

Rearranging the integration order and naming, we have

$$\gamma(x-x') = \int s(x'-\xi)s'(x-\xi)d\xi = \int s(\nu)s'(\nu+(x-x'))d\nu . \quad (3)$$

Then we have

$$o(x) = \int g(x')h(x-x')\gamma(x-x')dx' = \int g(x')h'(x-x')dx' = g(x) \otimes h'(x) . \quad (4)$$

Equation (3) expresses the final reconstructed image as a convolution with the impulse response associated with the full process, which is

$$h'(x) = h(x)\gamma(x) . \quad (5)$$

The function *γ(x)* is the correlation between the encoding and decoding masks. In the case that both coincide, it reduces to the autocorrelation of the encoding mask. When the encoding pattern is a random distribution, the autocorrelation will be a function highly concentrated at

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the origin. If, furthermore, the autocorrelation peak is small as compared with the lens impulse response, the autocorrelation can be approximated by a delta function, giving

$$h'(x) \simeq h(x)\delta(x) = h(0)\delta(x). \tag{6}$$

Under these assumptions, a high resolution image is reconstructed according to Eq. (4).

Let us recall the characteristic of a speckle pattern as the one generated, following Fig. 1, in the sample plane. The autocorrelation of a speckle pattern is given by the Fourier transform of the intensity distribution at the diffuser plane scaled according to the distance between the diffuser and the observation plane [18]. For a rectangular aperture with size L at a distance z, the ensemble average correlation becomes

$$\gamma(x) = sinc^2\left(\frac{Lx}{\lambda z}\right) \tag{7}$$

The size of the main lobe of the autocorrelation is $\Delta = 2\lambda z / L$. This will be the resolution spot size in the reconstructed image. Defining $A = 2z / L$, which is the "equivalent numerical aperture" of the diffuser, the previous condition in order to be able to apply Eq. (6) reads as $A \gg NA$. Under this restriction the resolution of the full process is now given by this effective aperture and is independent of the lens resolution. The extreme case would be a pinhole imaging, without a lens, where the impulse response is uniform, but still the resolution associated with the speckle pattern is obtained.

The above discussion has been made for the coherent case. An interesting practical application is the use of the method for fluorescence microscopy, where the speckle pattern is converted into an intensity on the sample plane. The derivation of the output when the same procedure is applied to fluorescence imaging is analogous to the coherent case. The main difference is that the relevant magnitude is the intensity. Naming $I_g(x)$, $I_s(x)$ and $I_h(x)$ the intensity distributions for the input, speckle pattern, and impulse response, respectively, the output can be now expressed as

$$o_{incoh}(x) = I_g(x) \otimes \left[I_h(x)\Gamma(x)\right], \tag{8}$$

$\Gamma(x)$ being the autocorrelation of the intensity of the speckle pattern. Following Ref. [18], this function is, except for constants

$$\Gamma(x) = \left[1 + sinc^2\frac{Lx}{\lambda z}\right]. \tag{9}$$

Under the same assumptions that were stated above, the second term can be approximated by a delta function. The output will be an addition of the low resolution image and the superresolved image

$$o_{incoh}(x) = I_g(x) \otimes I_h(x) + I_g(x). \tag{10}$$

A simple processing, in order to remove the low pass version is thus needed.

3. Experiments

The viability of the proposed method has been demonstrated in laboratory experiments. The experiments demonstrate that, after a proper calibration, a limited aperture lens can provide a similar resolution as a high NA lens.

The experiments are made on an Olympus BX61 epi-fluorescence microscope, using 10x and 20x 0.4 NA Olympus LCPlanFl. The images are grabbed with 12 bits per pixel camera (Roper Scientific CoolSnapHQ). The sample is the central portion of a spoke target, presenting a continuous range of spatial frequencies. The experiments are made by coherent illumination using an Argon laser at 488 nm wavelength. The speckle pattern is obtained by expanding the laser beam and impinging on a plate of translucent perpex, which acts as an opal diffuser, with unnoticeable grain and nearly Lambertian scattering of the light. In the fluorescence experiments the sample is coated with a thin layer (~5 μm) of solution of fluorescein diacetate (FDA) that reemits incoherent light in the green wavelengths of the optical spectrum.

The process requires a high resolution image of the speckle that acts as the encoding-decoding mask. We take these reference images prior to each experiment by focusing at a transparent region in the sample plane using a lens with high NA (0.4). Figure 2 displays the reference image and its autocorrelation. The size of the autocorrelation peak is the expected resolution after the superresolution process when a low NA lens is used.

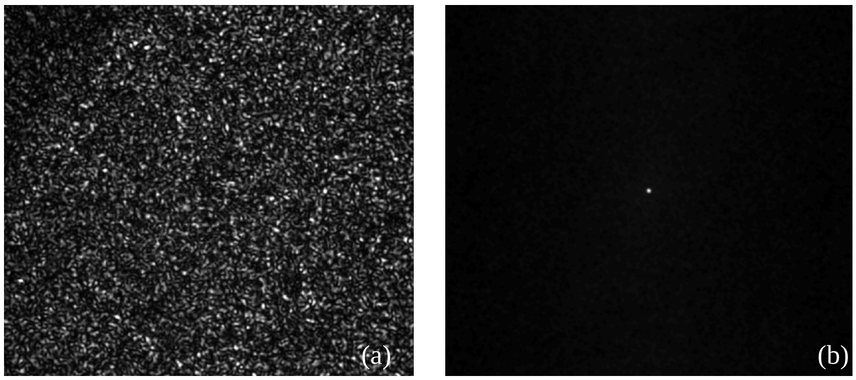

Fig. 2. (a) Encoding speckle pattern. (b) Autocorrelation of the encoding pattern.

Once the reference speckle pattern is captured, the sample is set in place and the lens is replaced by a lens with a low NA in the horizontal direction. Then the sample position is laterally scanned and the image set is captured. Note that instead of displacing the projected pattern (or, equivalently, the diffuser) and the decoding pattern synchronously, we instead scan the sample position and keep the encoding and decoding masks static. The situation is fully equivalent, provided that the captured images are shifted digitally, to compensate the mechanical movement of the sample. The discrete sampling affects the autocorrelation that determines the impulse response of the process. Thus in Eq. (3) the integral becomes a summation and the variable ξ is discretized. The correlation is obtained by spatial averaging; thus the minimum shift should be similar to the correlation run length of the speckle pattern (otherwise the contribution of different samples would coincide). The span between extreme samples should be significantly larger than the speckle size, for obtaining sufficient statistical averaging. The larger the number of samples the better will the correlation estimation be (typically a few tenths should suffice).

We capture a set of 60 images. Each one is multiplied by the previously recorded high resolution speckle pattern and the resulting images are added together. Figure 4(a) shows a sample image captured with the low resolution lens. No information can be observed on it. The typical horizontal speckle size is related with the lens resolution and is too large to resolve the pattern in the sample. Figure 4(b) displays the reconstructed image. Although speckle noise corrupts the image, the sample can be clearly distinguished. The movie associated to the figure shows how the reconstruction is built over time as subsequent frames are added. This movie gives also a direct visual interpretation of the underlying principle in the method. Note that, despite of the large speckle size, the speckles are blinking as the pass the different transmittance areas of the sample. This information is decoded using the same mask that was blurred by the low NA lens and recovers the resolution of the high resolution encoding mask.

Finally, we performed a similar test but after covering the sample with a thin layer of FDA. This converts the speckle pattern in the sample into an incoherent distribution. Figure 5

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shows a sample low resolution image and the reconstructed image. The resolution of the low NA lens is now higher, owing to the incoherent sample illumination. Still, the higher frequencies of the pattern cannot be resolved and the low ones have a low contrast. After applying the superresolution method here proposed, we can clearly observe the fine lines in the pattern and the increased contrast and crispness in the low frequency areas.

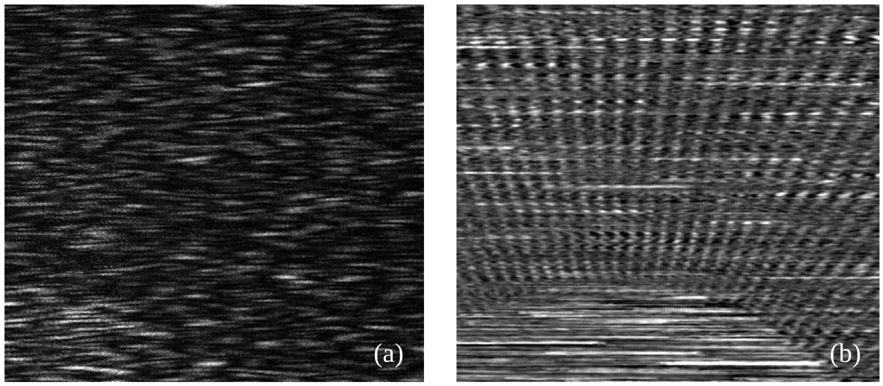

Fig. 3. (a) Low pass image. (b) Reconstruction from the image set (1.34 MB).

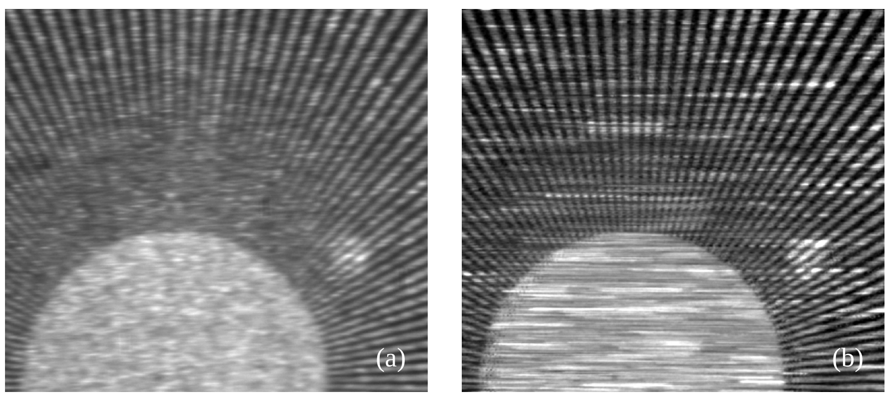

Fig. 4. Incoherent case. (a) Low pass image (b) Reconstruction from the image set (888 KB).

4. Conclusions

We have presented and experimentally demonstrated a method for superresolution based on projection of a high resolution speckle pattern of the sample. As a calibration of the system, a high resolution image of the projected speckle pattern must be taken. The final resolution is that of the projected pattern in this high resolution image, and it is independent of the numerical aperture (NA) of the lens used thereafter. Thus, even a pinhole lens could be used. A main advantage of the method is the simplicity of the illumination system (a conventional diffuser) that does not need any projection system or high resolution structured patterns.

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