Superresolution using gray level coding

Zeev Zalevsky

School of Engineering, Bar-Ilan University, Ramat-Gan 52900, Israel
zalevsz@eng.biu.ac.il

Pascuala García-Martínez, and Javier García

Departamento de Óptica, Universitat de Valencia, c/Dr. Moliner, 50, 46100 Burjassot, Spain

Abstract: In this paper we describe a super-resolving approach based upon gray level coding of the information. Thus, the imaged object should have limited number of gray levels. The proposed approach overcomes the resolution limitations caused either by the optics or by the finite size of the detector. In contrast to other existing super resolution techniques that use time or wavelength multiplexing, in this approach one does not need to pay neither in temporal nor in wavelength degrees of freedom, but in intensity dynamic range. After the gray coding and the imaging, the high frequency spatial resolution features are decoded using the decoding gray level lookup table.

OCIS codes: (100.6640) Superresolution; (070.4560) Optical data processing.

References and links

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1. Introduction

Super resolution is one of the most fascinating and applicable fields in optical data processing. The urge to obtain highly resolved images using low quality imaging optics and detectors is very appealing. The field of super resolution may be categorized into two groups: diffractive and geometrical super resolution. The first one deals with overcoming the resolution limits dictated by the diffraction laws and are related to the numerical aperture of the imaging lens. The second field overcomes the limitation determined by the geometrical structure of the detector array. Various techniques have been developed to deal with both types of resolution improvements [1-3]. In all approaches the spatial resolution improvement needs that the object exhibits some sort of constraint (such as monochromaticity, slow variation with time, single polarization …), related with an unused dimension of the object. The improvement is thus made at the price of sacrificing unused degrees of freedom in the other domains as time

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[4, 5], wavelength [6], polarization [7] or field of view [8]. To the best of our knowledge the intensity dynamic range degree of freedom has never been used for achieving superresolution.

In this paper we present an approach in which significant resolution improvement factor is possible. The technique provides resolution improvement for both diffractive as well as geometric limitations. The required constraint is that the object has limited number of gray levels and thus the gray level domain can be used in order to code and decode the additional spatial information. A very interesting application in which the presented super resolving coding may be applied is related to geometrical rather than diffractive super resolution.

2. Basic theory

We start with presenting the theory of the gray coding for super resolution. As can be seen from the derivation this approach is good for both geometrical as well as diffractive resolution enhancements.

Let's assume that *p(x,y)* is the blurred point spread function whose blurring is caused due to the combination of the limited aperture of the optics and the area of each pixel in the detection array. The blurred image is sampled by the detection array. We assume that δx and δy are the sampling pitch in the horizontal and vertical axes respectively and that Δx and Δy are the horizontal and the vertical dimensions of the pixels in the detection array, respectively. Thus, the sampled image equals to:

$$I_o(x,y)=\int_{-\Delta x/2}^{\Delta x/2}\int_{-\Delta y/2}^{\Delta y/2} I_{in}(x',y')C(x',y')p(x-x',y-y')dx'\,dy'\sum_n\sum_m \delta(x-n\delta_x,y-m\delta_y) \quad (1)$$

where *C(x,y)* is the gray level coding mask. The last equation equals to:

$$\begin{aligned}I_o(n\delta_x,m\delta_y)=\sum_n\sum_m&\left[\int_{n\delta_x-\theta_x/2}^{n\delta_x+\theta_x/2}\int_{m\delta_y-\theta_y/2}^{m\delta_y+\theta_y/2} I_{in}(x',y')C(x',y')p(n\delta_x-x',m\delta_y-y')dx'\,dy'\right]\\&\times\delta(x-n\delta_x,y-m\delta_y)\end{aligned} \quad (2)$$

where θ_x and θ_y are the horizontal and the vertical dimensions of the blurring function, *p(x,y)*, respectively. For the simplicity of explanation we will assume that the input object I_{in} is a binary function having resolution coinciding with the detectors sampling grid δx and δy:

$$I_{in}(k_1\delta_x,k_2\delta_y)=\{0,1\} \quad (3)$$

In addition we will assume that *p(x,y)* is a rect function:

$$p(x,y)=rect\left(\frac{x}{\theta_x},\frac{y}{\theta_y}\right) \quad (4)$$

where $\theta_x=N\delta_x$ and $\theta_y=M\delta_y$, *N* and *M* are integer numbers.

The gray level coding mask is chosen such that:

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$$C(x,y)=\left[\sum_{k_1=n-N/2}^{n+N/2-1}\sum_{k_2=m-M/2}^{m+M/2-1}2^{k_1+N/2-n}\cdot 2^{k_2+M/2-m}rect\left(\frac{x-k_1\delta_x}{\delta_x},\frac{y-k_2\delta_y}{\delta_y}\right)\right] * \delta\left(x-nN\delta_x,y-mM\delta_y\right) \tag{5}$$

Thus, the output intensity equals to:

$$I_o(n\delta_x,m\delta_y)=\sum_{k_1=n-N/2}^{n+N/2-1}\sum_{k_2=m-M/2}^{m+M/2-1}I_{in}(k_1\delta_x,k_2\delta_y)\cdot 2^{k_1+N/2-n}\cdot 2^{k_2+M/2-m} \tag{6}$$

The meaning of the last equations is that the coding mask is chosen such that it is actually the binary base and thus after the blurring function the gray level of the blurred pixel equals to a different gray level. For instance, assuming that the super resolution should be of a factor of 2 in each dimension, i.e. N=2 and M=2 then the coding mask will be a periodic structure with super pixels constructed out of blocks with gray level of 1, 2, 4 and 8 as it is shown in Fig. 1(a). After the blurring and assuming that I_{in} is a binary object, the resulted gray level will indicate the spatial structure of I_{in} prior to blurring. In Fig. 1(b) one may see a look up table connecting the spatial structure of I_{in} in the super pixel prior to blurring and the resulted gray level, when the structure is multiplied by the gray level coding mask and integrated over a super pixel [Eq. (6)].

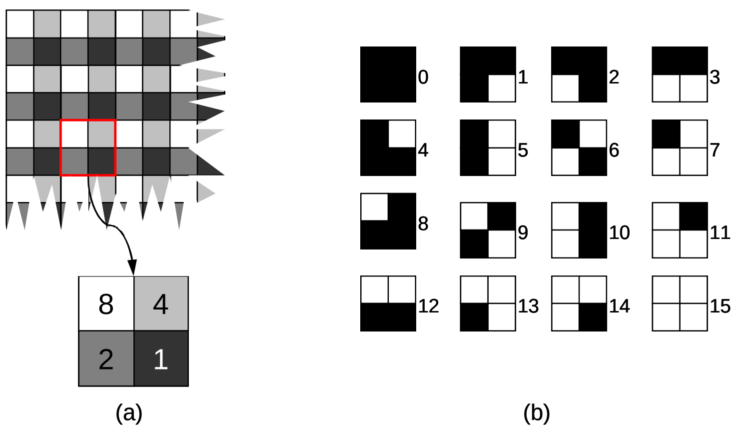

Fig. 1. (a). The gray level coding mask. (b) The look up table relating sensed gray level and the spatial structure of the original object.

3. Experiments

The experimental setup is depicted in Fig. 2. Spatial light modulator (SLM) was attached to a binary object. The gray coding mask was displayed on the SLM. The light passing through the object and the mask was imaged on top of a camera. For the purpose of demonstration we have used binning in the detector to simulate a low resolution device. This permits to record also a high resolution version for comparison.

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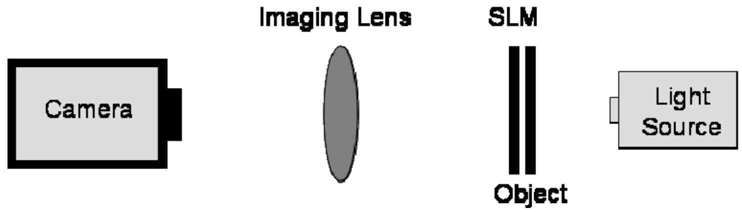

Fig. 2. The experimental setup.

A binning of 1 by 5 was performed in the camera. The coding mask displays gray values of 1, 2, 4, 8 and 16. The imaged object seen by the camera without applying the binning (high resolution) is presented in Fig. 3.

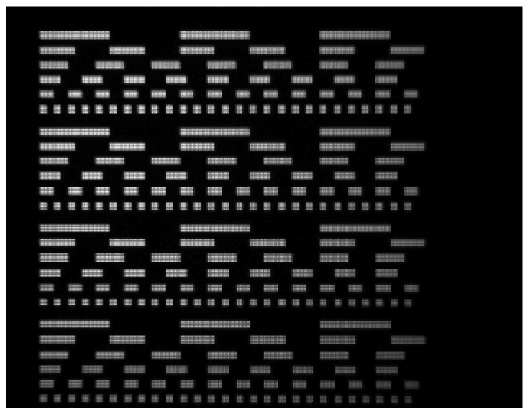

Fig. 3. The high resolution image.

Figure 4(a) presents the image seen by the camera after applying the binning. One may see that most of the spatial content of the object is lost due to the binning low pass effect. In Fig. 4(b) we display the experimentally reconstructed image after the gray levels decoding. One may see that although some reconstruction errors occurred in the first three lines of the decoded object, except of that the original spatial resolution of the object was reconstructed.

Note that the suggested gray coding that translates the captured gray level into resolution of the original image is a very simple code. This code is not immune to errors. This is something which is very non-recommendable since small error in the gray level may change completely the decoding pattern (see for instance the variations of the decoded patters versus the gray level as seen in Fig. 1(b)). However, it is very simple to use an optical code that is much more immune to gray level errors. One example can be the Gray codes [9]. In those codes the change between two adjacent codes has variation of only 1 bit and thus errors in the gray level will cause minimal spatial distortion (distortion of only 1 bit).

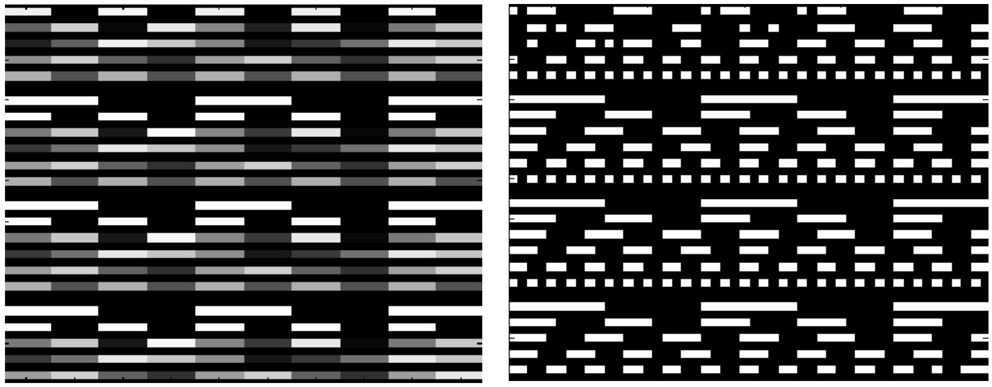

Fig. 4. a). The experimentally grabbed image after binning and before decoding. b). The experimentally reconstructed image after gray levels decoding.

4. Discussion and conclusions

The presented approach is modular and may be used in the same manner for 1-D as well as 2-D super resolution. It does not require "payment" in the time or the wavelength axes as other super resolving approaches tend to do. Instead the dynamic range on the intensity (the number of distinct gray levels) degree of freedom is used. Eventually, the dynamic range of the system (related to its signal to noise ratio) will limit the possible superresolution enhancement. Because of this, the method takes the maximum advantage when the input object is binary, letting the full intensity dynamic range available for coding. For binary input case, every new resolution element in the coding mask needs and additional bit in the system dynamic range. In most practical cases, the dynamic range is limited either by the photodetection noise or by the sensor dynamic range. A figure of 9 bits (512 distinct gray levels) can be achieved in most common imaging systems, giving a 9 times increase of the resolution. Thus for the 2-D case a factor of 3 on each axis can be obtained.

In summary in this paper we have demonstrated a new approach for super resolution. The suggested approach is based upon coding the blurred spatial information of the imaged object using gray level coding. The approach is very modular and can be used for 1-D as well as 2-D super resolution. It can match diffractive as well as geometrical super resolution needs.

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