Plenoptic Camera Resolution

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Abstract: To resolve the low resolution problem of Plenoptic cameras we analyze optical signal sampling at frequencies above Nyquist. The resultant aliased signal is superresolved interleaving the array of microimages, thus cancelling the aliasing components. The rendered image can reach full sensor resolution.
OCIS codes: (100.6640) Superresolution; (110.1758) Computational imaging; (110.5200) Photography; (110.4190) Multiple imaging;

1. Introduction

The Plenoptic camera (see Fig 1) is a universal phase space sampling device. It measures the radiance, i.e. captures ray intensities in 4D optical phase space. In comparison traditional cameras simply measure the irradiance, i.e. record 2D image pixels. Recent lightfield research [1-4] demonstrates a number of results impossible with traditional cameras, including image refocusing after capture, stereo and multi-view stereo with single camera, HDR and multimodal imaging. Commercialization efforts made by companies like Raytrix and Lytro bring the plenoptic camera closer to the goal of replacing the traditional camera in photography and possibly in in imaging, in general.

There is, however, a significant obstacle to making the plenoptic camera competitive in the market. That's the extremely low resolution of the final rendered image. Typically the final image has 40X lower resolution than the resolution of the image sensor, measured in megapixels [5]. This makes the plenoptic camera look inferior compared to the traditional digital camera. It appears that either we have to use current image sensors and accept the reduced resolution, or we have to use extremely high resolution sensor at high cost. Neither of those is acceptable.

In this paper we are looking at another option: Superresolution [6, 7]. We analyze the plenoptic data capture process in frequency domain and demonstrate that not only resolution can be improved without introducing artifacts, but that it can actually reach the original sensor resolution.

2. Basic setting and formulas

To simplify our formulas, and without loss of generality, we will consider only 1D images. Based on microlenses, the plenoptic camera captures an array of microimages, one for each microlens. We assume relay imaging model (i.e. plenoptic 2.0 camera), where each microlens remaps part of the main lens image to the sensor, acting as a little camera re-projecting the in-camera radiance from its own perspective.

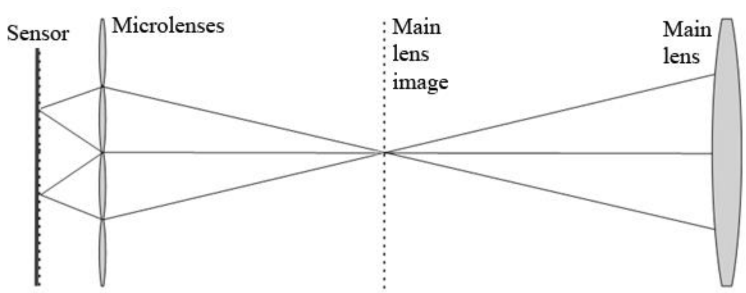

Fig. 1 The main lens creates the main lens image, parts of which are mapped to the sensor by individual microlenses.

First we describe the formation of one separate microimage. Assuming pixel pitch p and pixel size ε, we represent the image convolved with the pixel response function, and periodically sampled, as $g = (f * \Pi_\varepsilon)\cdot Ш_p$ where $f(x)$ is the optical image, $\Pi_\varepsilon(x)$ is the pixel response function, $Ш_p(x) = \Sigma\, \delta(x-np)$ is the Dirac comb with peaks at the centers of pixels, and $*$ is the convolution. We will denote the Fourier transforms of f and g by F and G respectively. Also u will be the independent frequency variable, and the Fourier transform of $\Pi_\varepsilon(x)$ will be assumed to be $sinc(\pi\varepsilon u) = sin(\pi\varepsilon u)/(\pi\varepsilon u)$. Using these notations, after Fourier transform the captured image is represented as

$$G(u) = (F(u)\cdot sinc(\pi\varepsilon u)) * \frac{1}{p}\text{Ш}_{\frac{1}{p}}(u) \qquad (1)$$

Usually pixel size is assumed to be the same as the pixel pitch, i.e. $p = \varepsilon$, and also $F(u)\cdot sinc(\pi\varepsilon u)$ is assumed essentially zero for frequencies above the Nyquist, i.e. above $1/(2p)$. This avoids aliasing. See Fig 2.

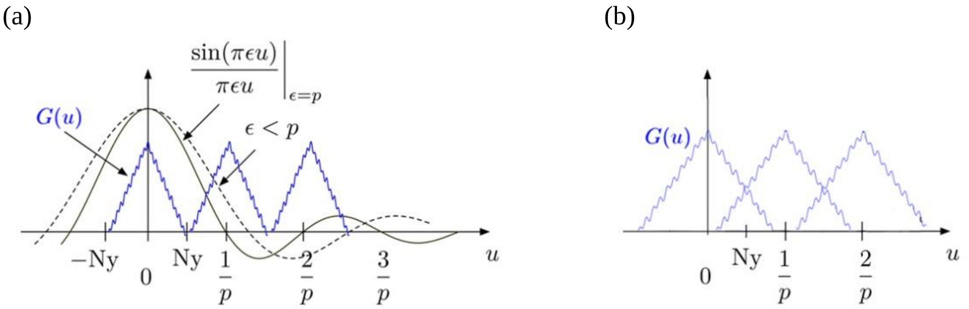

Fig 2 (a) G(u) is periodic with period 1/*p* due to the convolution with Dirac comb. The central piece fits within the Nyquist bandwidth so there is no aliasing. G(u) is generated from F(u) by modulation with the sinc function, thus reducing the bandwidth. However (see dotted curve) for smaller and smaller pixel size the bandwidth can increase unlimitedly as ε decreases. (b) If pixel size is small and the optical signal has high bandwidth, we observe aliasing in the microimages.

For this paper we will assume that the highest frequency to which pixels can respond reliably beyond the noise level is determined by the location of first zero of the sinc function, which is at $1/\varepsilon$. When $\varepsilon = p$ the signal is limited to no more than two times the Nyquist frequency. The related superresolution cannot achieve more than 2X increase in resolution. However if we use a mask to limit the optically active pixel area to $\varepsilon < p$, the width of the sinc function increases and we can sample unlimitedly high frequencies as ε gets smaller. Unfortunately, the signal becomes severely aliased and not usable directly for imaging.

3. Superresolution removes aliasing

To introduce our approach first consider computing the sum of two aliased microimages containing frequencies up to two times higher than the Nyquist, and shifted by half pixel relative to each-other. In the frequency domain such shift corresponds to a phase multiplier $e^{i\pi pu}$. As a result adding two such images cancels the component centered at $u = 1/p$, see Fig 2(b). This effect may be viewed as "interference in the frequency domain" that removes aliasing. Actually this process cancels all copies of the signal shifted by $1/p$, $3/p$, $5/p$, …

Similar effect takes place with three images shifted by $p/3$ relative to each-other. Cancellation comes because of the identity $1 + e^{i2\pi/3} + e^{i4\pi/3} = 0$. The same can be shown with n images, each shifted by p/n relative to the previous one. In this way all aliasing is removed by superresolution.

This process opens up a very interesting possibility to increase the resolution of the rendered image from a plenoptic camera. Pixel size ε can be made as small as needed by using appropriate mask. The MTF of the lenses can be made much better than the typical Nyquist frequency of today's SLR cameras. The only limit is the sensor resolution itself. This makes it possible to build a plenoptic camera that has no loss in resolution, i.e. the final rendered image has the same resolution as the sensor.

4. Results

A wide range of experiments have been performed to confirm the above results. If optical bandwidth is sufficient to support given frequencies, those frequencies are represented in the final image, with no aliasing. See Fig 3.

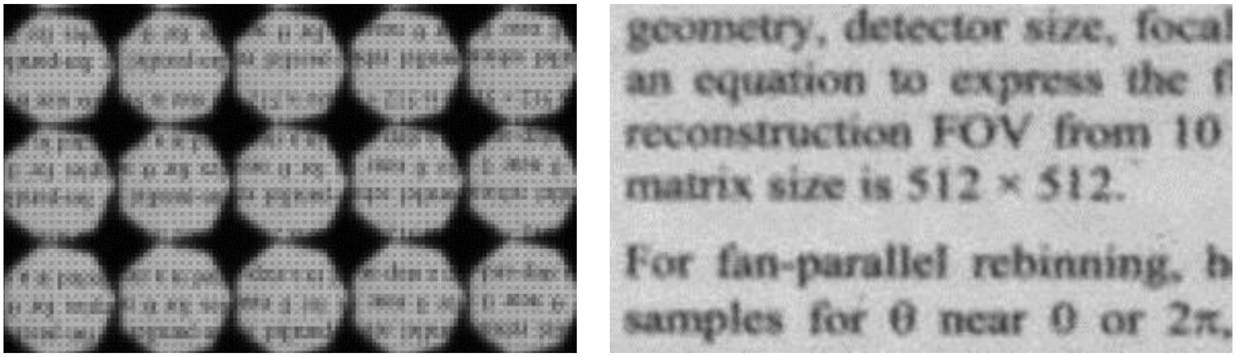

Fig. 3. Raw captured image (left), and the image rendered from it (right). Text is not readable in the raw image.

The F-number of the lenses is critical to provide high frequencies because of the related cutoff frequency in the MTF. This has been observed multiple times, especially when using cameras with small pixels at large F-numbers. Cutoff frequency is the only real limitation of the method described.

In conclusion, up to full sensor resolution of the final rendered image can be achieved with a plenoptic camera. One needs to take care of pixel size, mask pinholes and F/number of the lenses in order to achieve capture of frequencies as high as 6 times the pixel pitch – which would ensure $6^2 = 36$ times increase in resolution to cover the full resolution of the sensor. This can be done for example with 6 μm pixels and lenses working at F/1.

5. References

[1] R Ng, M Levoy, M Bredif, G Duval, M Horowitz, et al., "Light field photography with a hand-held plenoptic camera," Computer Science Technical Report CSTR(Jan 2005).

[2] R. Ng, "Fourier slice photography," ACM Trans. Graph., 735–744(2005).

[3] T. Georgiev, A. Lumsdaine, "Focused Plenoptic Camera and Rendering", Journal of Electronic Imaging, Vol 19, Issue 2, 2010.

[4] T. Georgiev, A Lumsdaine, G. Chunev, "Using Focused Plenoptic Cameras for Rich Image Capture", IEEE Computer Graphics and Applications (Jan 2011).

[5] T. Georgiev, Z. Yu, A. Lumsdaine, S. Goma, "Lytro Camera Technology: Theory, Algorithms, Performance Analysis", Proc. SPIE 8667, Multimedia Content and Mobile Devices, 86671J (March 7, 2013).

[6] T. Bishop, S. Zanetti, and P. Favaro, "Light field superresolution", Proceedings ICCP 2009.

[7] T. Georgiev, G. Chunev, A. Lumsdaine, "Superresolution with the Focused Plenoptic Camera", SPIE Electronic Imaging, Jan 2011.