Single-shot subpixel response measurement with an aperture array pixel mask

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We first point out that the subpixel response function is another kernel function in digital imaging. Then we show that the subpixel response function of CMOS imaging sensor pixels can be measured with an aperture array pixel mask in a single-shot image capture. Our technique permits high-resolution subpixel response function measurement of imaging pixels for superresolution imaging applications. © 2006 Optical Society of America

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High-resolution digital imaging has been desired for many applications such as medical diagnosis and remote sensing. The resolution of digital imaging systems is limited by the size of photodetector pixels. To increase the resolution of an imaging system, the most direct approach is to reduce the pixel size and increase the number of pixels. As the pixel size decreases, the available number of photons decreases, and the signal-to-noise ratio decreases because of the shot noise.[1] Also, transferring the data from the pixels becomes slow as the number of pixels increases.

Recently there is an increasing interest in synthesizing high-resolution images from multiple nonredundant low-resolution images by taking advantage of the inexpensive signal processing capability in the electronics world.[2] Several techniques have been proposed to overcome the pixel size limitation to achieve superhigh-resolution imaging.[3,4] One technique is to use multiple subpixel shifted images to synthesize the superhigh-resolution image.[5,6] Another technique is to use subpixel coded apertures to obtain the superhigh-resolution image. Both techniques require preknowledge of the subpixel response function of the imaging pixels.

The subpixel response of imaging pixels is not constant crossing the pixel area. Sharma *et al.*[7] measured the subpixel response of near-infrared sensors by scanning a focused subpixel size beam over a single pixel. With a similar beam scanning technique, a nonuniform subpixel response of coupled-charge devices (CCDs) has been reported.[8,9] The resolution of the subpixel response measurement by using the focused beam scan is fundamentally limited to the diffraction limit. Also the focused beam scanning technique requires complicated optical setups to precisely control the beam position.

Here we demonstrate a new technique for measuring the subpixel response by using a pixel mask. Our technique requires only a single-shot image capture. Since all the imaging pixels are identical and arranged periodically, an aperture array pixel mask can be designed to map different locations of the pixels. We treat the pixels as the optical sampling windows and measure how the optoelectrical response changes inside a pixel. The aperture size on the pixel mask can be much smaller than the diffraction limit. Therefore the technique can give very high-resolution measurement of the subpixel response function. In this Letter, we first show that measured digital imaging signals are related to the object field through two kernel functions: impulse response function of the imaging system and the pixel response function of the imaging pixels. Then we show that the subpixel response function of CMOS sensor pixels can be obtained by using an aperture array pixel mask with a single-shot image capture. To our knowledge, this is the first subpixel response mapping with a single-shot image capture.

Most optical imaging systems are linear systems. In a linear optical imaging system, the image $i(x,y)$ and the optical representation of an object $o(x',y')$ are related as

$$i(x,y) = \iint_{|x'|<\infty, |y'|<\infty} o(x',y')h(x,y;x'y')\mathrm{d}x'\mathrm{d}y', \quad (1)$$

where $h(x,y;x',y')$ is the impulse response of the imaging system. In a digital imaging system, the signal from the pixel (m,n) is

$$D(m,n) = \iint_{|x|<\infty, |y|<\infty} s(x-mb,y-nb)i(x,y)\mathrm{d}x\mathrm{d}y, \quad (2)$$

where b is the pitch of the imaging pixels and $s(x,y)$ is the pixel sampling function. $s(x,y)=p(x,y)$ for $|x| \le b/2$ and $|y| \le b/2$; $s(x,y)=0$ for $|x|>b/2$ and $|y|>b/2$. Here $p(x,y)$ is the pixel response function. Substituting Eq. (1) into (2) and replacing $s(x,y)$ with $p(x,y)$, the electrical signal from the pixel (m,n) is

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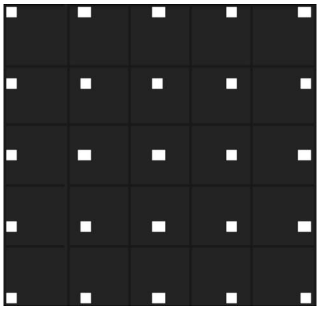

Fig. 1. Subpixel aperture pattern on the pixel mask.

$$D(m,n) = \iint_{\substack{\left(m-\frac{1}{2}\right)b<x<\left(m+\frac{1}{2}\right)b \\ \left(n-\frac{1}{2}\right)b<y<\left(n+\frac{1}{2}\right)b}} p(x-mb,y-nb)\mathrm{d}x\mathrm{d}y \times \iint_{|x'|<\infty,|y'|<\infty} o(x',y')h(x,y;x',y')\mathrm{d}x'\mathrm{d}y. \quad (3)$$

Equation (3) shows that measured imaging signals are related to the object field through both the impulse response function of the imaging system and the pixel response function of the imaging pixels.

We use an aperture array pixel mask to measure the pixel response function. The transmission intensity profile of a subpixel aperture at the origin is $a(x,y)$. At the pixel (m,n), it is shifted to $a(x-md, y-nd)$, where d is the pitch of the aperture array on the mask. The pixel mask is placed in direct contact with the pixels. Since the location of the subpixel aperture relative to the pixel shifts a small amount, $\delta=(d-b)$, from one pixel to the adjacent pixel, the subpixel response can be mapped by a single-shot image capture. We illuminated the masked pixels with a uniform light. The electrical signal measured by the pixel (m,n) is

$$D(m,n) = C\iint_{\substack{\left(m-\frac{1}{2}\right)b<x<\left(m+\frac{1}{2}\right)b \\ \left(n-\frac{1}{2}\right)b<y<\left(n+\frac{1}{2}\right)b}} a(x-md,y-nd) \times p(x-mb,y-nb)\mathrm{d}x\mathrm{d}y, \quad (4)$$

where C is a constant. Shifting the coordinate origin to the center of the pixel (m,n) by using variable transforms of $u=x-mb$ and $y=v-mb$, we have

$$D(m,n) = \iint_{\substack{-b/2<u<b/2 \\ -b/2<v<b/2}} a(u-m\delta,v-n\delta)p(u,v)\mathrm{d}u\mathrm{d}v, \quad (5)$$

where $\delta=(d-b)$. Equation (5) shows that $D(m,n)$ is the measurement of pixel response function $p(x,y)$ with a subpixel sampling function of $a(x,y)$ sampled at the discrete location $(m\delta,n\delta)$. To avoid aliasing, the size of the subpixel apertures should be smaller than or equal to δ.

The imaging sensor we used was a monochrome CMOS imaging sensor with a total of 1280×1024 pixels. The pitch of the pixels is 5.2 μm in the two directions. The pixel mask was a chrome mask (120 nm thick chrome on a 0.5 mm thick glass substrate). There is a two-dimensional array of 1 μm square apertures on the mask. The pitch of the aperture array is 6.2 μm in two directions. The pixel mask was in direct contact with the CMOS pixels. The orientation of the aperture array was aligned with the orientation of the pixel array of the CMOS sensor. Figure 1 is the subpixel aperture pattern on the pixel mask. The relative location of the subpixel aperture shifts from one pixel to another pixel, which allows different apertures to probe the subpixel response at different locations.

In our experiment, the illumination light was generated by filtering an incandescent broadband light with a 10 nm bandpass filter at 660 nm. The illumination light was first collimated and then vertically illuminated to the masked CMOS pixels with a uniform spatial intensity. A single-shot image frame was captured by a computer. The variation of the measured electrical signal from one pixel to another indicates the nonuniform pixel response crossing the pixel area. Since the relative shift from one aperture to the adjacent one is 1 μm, the mapping resolution is 1 μm. We take a 12×12 data matrix from 12×12 pixels. A 12×12 data matrix corresponds to a mapping area of $12\,\mu\text{m}\times12\,\mu\text{m}$. An area of $12\,\mu\text{m}\times12\,\mu\text{m}$ covers approximately 2×2 pixels. We plotted the subpixel response versus the relatively shifted distance in Fig. 2. The vertical axis is the normalized subpixel response function calculated from the single-shot image capture. The subpixel response has the same physical meaning as the quantum efficiency, which is unitless. From Fig. 2 we see a 2×2 array of a repeatable pattern. A single pattern in Fig. 2 is the subpixel response mapping of a CMOS pixel. It clearly shows that the subpixel response reaches the maximum in the center of each pixel.

Higher-resolution pixel response mapping can also be obtained by taking advantage of the small residue shift of the subpixel apertures relative to the pixels.

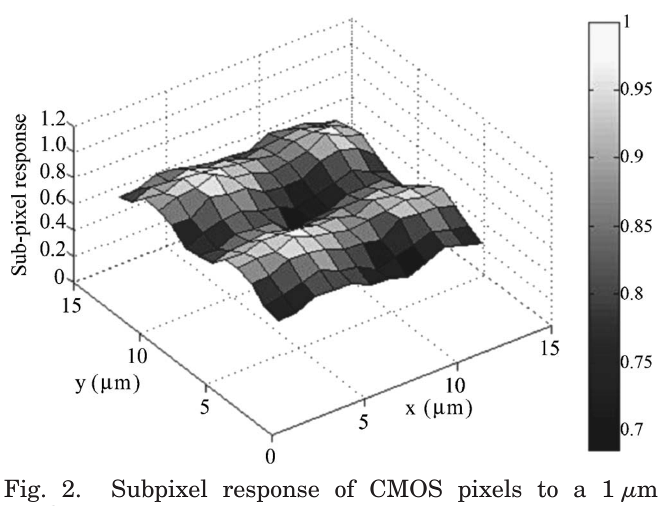

Fig. 2. Subpixel response of CMOS pixels to a 1 μm resolution.

We take $N = \lfloor b/\delta \rfloor$, where $\lfloor b/\delta \rfloor$ is the greatest integer number smaller than b/δ. The residue shift for N pixel measurements $r = b - \delta\lfloor b/\delta \rfloor$. Here r is 0.2 μm; i.e., there is a 0.2 μm residue shift for every N pixel measurement. Because of this residue shift, the sampling position of the measurement $D(m+6,n+6)$ is shifted by a distance r with respect to the sampling $D(m,n)$ in two directions. The sampling position of the measurement $D(m+j6,n+j6)$ is shifted by a distance jr with respect to the measurement $D(m,n)$ in two directions $(j=1,2,3,4,5)$. The shift direction is the reverse of the direction of the increments of m and n.

First we take the captured data matrix of $N(N+1)\times N(N+1)$ $(N=5)$ and rearrange the data matrix $D(m,m)$ to $K(m,n)$ by using the equation

$$K(m,n) = D[N(N+1) - m + 1, N(N+1) - n + 1],$$

$$n = 1,2,3\ldots 30, \quad m = 1,2,3,\ldots 30. \tag{6}$$

The elements in $K(m,n)$ are in the reverse order with respect to the matrix $D(m,n)$. Rearranging $K(m,n)$ to $F(m,n)$, we have

$$F(m,n) = K\left\{1 + \left[\frac{m}{5}\right] + 6\times\left(m - 1 - 5\times\left[\frac{m}{5}\right]\right), 1 + \left[\frac{n}{5}\right] + 6\times\left(n - 1 - 5\times\left[\frac{n}{5}\right]\right)\right\},$$

$$n = 1,2,3\ldots 30, \quad m = 1,2,3,\ldots 30, \tag{7}$$

where $\lfloor m/5 \rfloor$ is the greatest integer smaller than $m/5$ and $\lfloor n/5 \rfloor$ is the greatest integer smaller than $n/5$. $F(m,n)$ is the pixel response function of a 0.2 μm sampling resolution. Figure 3 is the plot of normalized $F(m,n)$ versus the spatial location in a pixel. The vertical axis is the normalized subpixel response computed from the single-shot image capture. The response pattern shown in Fig. 3 repeats itself when we use a large data matrix.

In this Letter we first showed that the subpixel response function is an additional kernel function to the impulse response function for digital imaging systems. Then we showed a new technique to measure the subpixel response function of a CMOS imaging sensor with a single-shot image capture. The technique can be applied to any imaging sensor pixel measurement. A 1 μm resolution of the pixel response function of a CMOS sensor has been obtained. The subpixel response of 0.2 μm resolution has also been obtained by taking advantage of the 0.2 μm residue shift. The 0.2 μm resolution pixel response mapping has measurement aliasing, since the size of each aperture is 1 μm square. Further research is to develop an algorithm to remove the aliasing. Additional further research is to use smaller apertures to obtain higher-resolution subpixel response mapping.

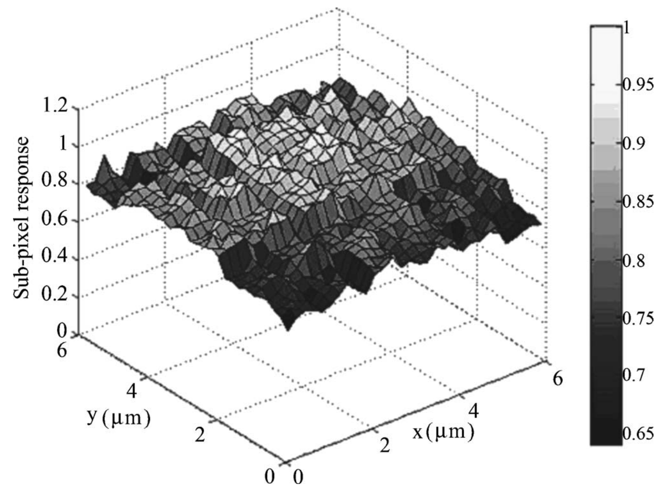

Fig. 3. High-resolution subpixel response of a CMOS sensor pixel.

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