Light energy matching method in high-resolution image reconstruction

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Many approaches for high-resolution image reconstruction have been proposed in some literatures. One of the most commonly ways is to reconstruct a high-resolution image from a number of rotated and translated images with low resolution. In this process, the exposure difference among original images will decrease the quality of the reconstructed image. In order to remove the influence of the exposure difference, a light energy matching method is proposed in this paper. The theoretical analysis is illustrated in details. Experimental results show that the theoretical analysis is correct and the proposed method is valid.

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In recent years, digital imaging technology has been applied in many fields, such as medicine, astronomy, architecture, industry measurement, satellite reconnaissance, remote sensing and so on. In some fields of applications, high resolution of digital imaging with more and more detail information is highly in demand.

A digital image is acquired by a detector array, such as CCD or CMOS sensors. The resolution of an image is limited by the total pixels of the detector array. Therefore, increasing the pixel number is the most direct way to improve the resolution. There have been two main approaches for increasing pixel number: (1) Reducing the pixel size is a traditional method. However, current semiconductor technology limits the reduction of pixel size. The smaller the pixel size is, the less the amount of light available for each pixel is. The image quality is poorer because of the existence of shot-noise[1]. (2) Combining patches of digital image to produce a large image is the other way[2]. But it needs a high combination precision. On the other hand, this method makes the optical design very difficult because of its large field angle. For these reasons, a set of digital imaging system with high resolution is usually very expensive.

In Ref. [3], a technique of the high-resolution reconstruction from a number of rotated and translated images with low resolution was proposed. The base of this technique is to acquire a sequence of rotated and translated original images and to get the accurate information of the rotation and translation. There are several kinds of systems for acquiring rotated and translated images, mainly based on two working principles. One is changing relative position between object and detector, and the other is changing relative position between image and detector by splitting optical path[4,5]. Different optical paths will lead to different transmittances. As a result, the luminous flux of image planes varies. The precision of the shutter will also lead to the variation in exposure time among these images. The problem of exposure difference will decrease the quality of the reconstructed image.

In this paper, we propose a light energy matching method to remove the influence of the exposure difference.

Figure 1 shows a digital imaging system. $P(x,y)$ is a point with brightness of L on the object plane. The illumination of point $P'(x',y')$ on the image plane corresponding to $P(x,y)$ can be calculated as

$$E = \frac{\pi}{4}\tau L\left(\frac{u-f}{u}\right)^2\left(\frac{D}{f'}\right)^2\cos^4\theta, \tag{1}$$

where τ is transmittance of the optical system[6].

The light energy absorbed by the CCD element on $P'(x',y')$ is

$$W = E\cdot\Delta S\cdot t, \tag{2}$$

where ΔS is the area of the CCD element and t is the integration of the exposure time[7].

Using Eqs. (1) and (2), we can acquire a digital gray image of the object

$$\begin{aligned} g(x,y) &= \alpha W \\ &= \frac{\pi}{4}\alpha\Delta St\tau\left(\frac{u-f}{u}\right)^2\left(\frac{D}{f'}\right)^2\times\cos^4\theta L(x,y) \\ &= KL(x,y), \end{aligned} \tag{3}$$

where α is a constant coefficient and $K = \frac{\pi}{4}\alpha\Delta St\tau\left(\frac{u-f}{u}\right)^2\left(\frac{D}{f'}\right)^2\cos^4\theta$.

The process of high-resolution image reconstruction can be described as

$$f(x,y) = T[C_1(x,y), C_2(x,y),\cdots,C_n(x,y)], \tag{4}$$

where $C_1(x,y), C_2(x,y),\cdots,$ and $C_n(x,y)$ are a sequence of slightly translated and rotated coarse (or

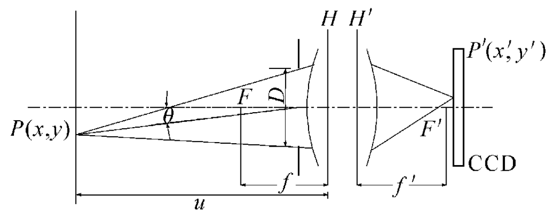

Fig. 1. Schematic of the digital imaging system, showing the relation between object and image.

low-resolution) gray images, and $f(x,y)$ is a fine (or high-resolution) image reconstructed from these coarse images. T is a reconstruction rule. For the purpose of getting original coarse image $C_i(x,y)$, one method is to slightly change relative position between object and image. The key of this method is to split optical path by changing the optical system.

Theoretically, the coarse images must be equal in gray levels because they share the same object. In other words, the light energy absorbed by CCDs should be the same among these coarse images. Otherwise, the quality of the reconstructed high-resolution image would decrease. This condition can be written as

$$\sum C_1(x,y)\Delta S_1 = \sum C_2(x,y)\Delta S_2 = \cdots = \sum C_n(x,y)\Delta S_n, \quad (5)$$

where $\Delta S_1, \Delta S_2, \cdots$, and ΔS_n are area of the CCD element, respectively.

Ideally, K in Eq. (3) is a constant for a certain optical system, and the Eq. (5) can be satisfied easily. However, K usually is not an exact constant, and it is also difficult to calculate transmittance τ accurately due to the complication and instability of optical system in the image acquiring process. This problem is particularly severe when we acquire original images by the method of splitting optical path, because the rays travel through different parts of the aperture in optical system. On the other hand, the instability of mechanical and electronic shutter makes the integration of each exposure time t unequal. Therefore, the practical coarse image is $C'(x,y) = \beta C(x,y)$, where $\beta(\neq 1)$ is a constant and $C(x,y)$ is the ideal image. Without loss of generality, suppose $C'_1(x,y) = \beta C_1(x,y)$. We have

$$f_d(x,y) = T[\beta C_1(x,y), C_2(x,y), \cdots, C_n(x,y)]. \quad (6)$$

Comparing Eq. (6) with Eq. (4), $f_d(x,y)$ is not the proper result we expect. This is the reason why the quality of the reconstructed high-resolution image decreases.

There are some approaches to reduce the above influence. One direct way is to get the value of τ by measuring a standard object beforehand, and adopting more perfect shutter in the exposure system. But it is not realistic and convenient. Here, we proposed a new and practical method to reduce the influence of exposure difference.

Suppose coarse images $C_1(x,y), C_2(x,y), \cdots$ and $C_n(x,y)$ are different, and $C_1(x,y)$ is a standard image. By introducing matching coefficients $\xi_1, \xi_2, \cdots$ and ξ_n, we can have

$$\xi_1 = \frac{\sum C_1(x,y)\Delta S_1}{\sum C_1(x,y)\Delta S_1},$$

$$\xi_2 = \frac{\sum C_1(x,y)\Delta S_1}{\sum C_2(x,y)\Delta S_2},$$

$$\vdots$$

$$\xi_n = \frac{\sum C_1(x,y)\Delta S_1}{\sum C_n(x,y)\Delta S_n}, \quad (7)$$

where $\xi_1 = 1$ obviously, and

$$\sum C_1(x,y)\Delta S_1 = \sum \xi_2 C_2(x,y)\Delta S_2 = \cdots = \sum \xi_n C_n(x,y)\Delta S_n. \quad (8)$$

Using Eq. (4) and Eq. (8), we get

$$f'(x,y) = T[C_1(x,y), \xi_2 C_2(x,y), \cdots, \xi_n C_n(x,y)], \quad (9)$$

where $f'(x,y)$ is a reconstructed high-resolution image.

The above approach is named light energy matching method, since $\sum C_i(x,y)\Delta S_i$ can be considered as the total energy absorbed by a CCD detector array. It doesn't need transmittance measurement and expensive shutter. Only a little work of image processing is added before the reconstruction. Its compute time is negligible in comparison with that in the image reconstruction process.

Inversion analysis[8] is a comparatively concise and effective algorithm for high-resolution reconstruction. It combines several slightly translated coarse gray images to obtain a high-resolution image. Inversion analysis is used in the programming of the experiment.

In order to acquire original images satisfying inversion analysis, we have designed a setup for splitting optical path. Taking advantage of crystal birefringence, a beam of light is split into an o ray (ordinary ray) and an e ray (extraordinary ray), which are linearly polarized. There is a small distance between the two rays and their polarization directions are orthogonal. When we place two appropriate crystals behind the lens, we can acquire 4 slightly translated images one by one using a polarization analyzer. Figure 2 shows schematic illustration of the optical setup.

Figure 3 shows one of four images, $C_1(x,y)$, $C_2(x,y)$, $C_3(x,y)$ and $C_4(x,y)$, acquired by the above setup. About 300 TV line resolution is achieved. We reconstruct two high-resolution images with a resolution enhancement ratio of 1.5 in both horizontal and vertical directions from the four coarse images. Figure 4 is a reconstructed image without using the light energy matching method. It is obviously blurry due to the exposure difference. Only about 350 TV line resolution is achieved. Figure 5 is a reconstructed image using the light energy matching method. Here, $\Delta S_1 = \Delta S_2 = \Delta S_3 = \Delta S_4$, because only one CCD is used in our experiment. Then, a set of data, $\xi_1 = 1.0000$, $\xi_2 = 0.90292$, $\xi_3 = 1.13080$ and $\xi_4 = 0.88251$, is obtained using Eq. (7). The reconstruction result has obviously improved in comparison with that in Fig. 4. More than 400 TV line resolution is achieved.

The exposure difference has the bad influence on the quality of the high-resolution image reconstructed from

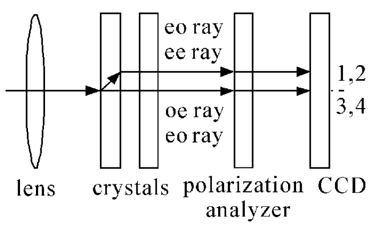

Fig. 2. Schematic of the optical setup.

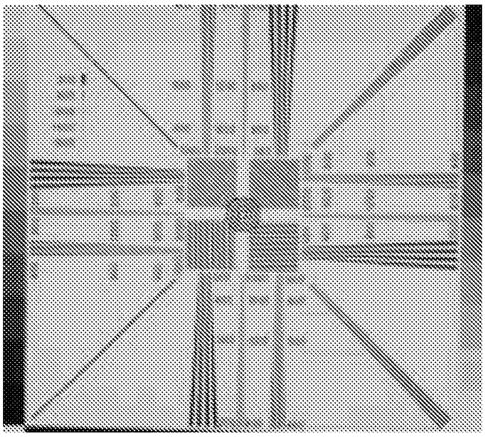

Fig. 3. One of four original images.

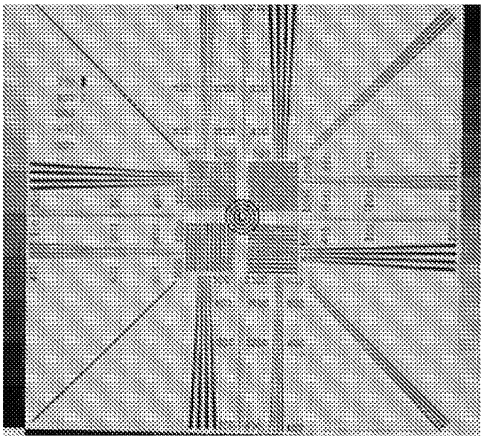

Fig. 4. An image reconstructed from original images without using the light energy matching method.

a number of translated and rotated images with low resolution. The light energy matching method we proposed here has been proved to be an effective and efficient way to reduce the influence of exposure difference. It can be regarded as the coarse image preprocess before the fine image is reconstructed.

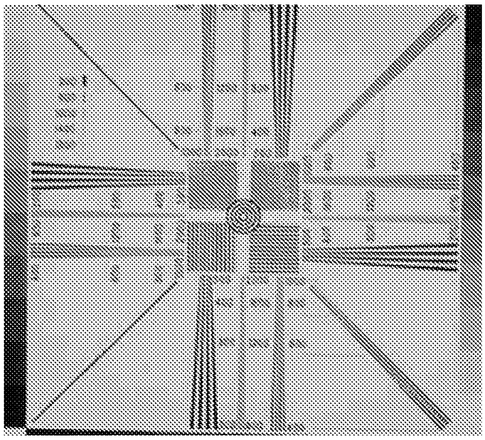

Fig. 5. An image reconstructed from original images using the light energy matching method.

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