Resolution progress of Image Sensor Over Nyquist Rate Using Digital Signal Processing and Optical Low-pass Filters

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Abstract

Two-dimensional images with frequency components higher than the Nyquist frequency of the image sensor were obtained using optical low-pass filters. 384x384-pixel images were reconstructed from four 192x192-pixel images. The reconstructed image had frequency components 1.5 times higher than Nyquist frequency of the charge coupled device (CCD) image sensor. The processing method described here can enhance the resolution of the conventional image sensor without requiring modification of the image sensor.

I. Introduction

Charge coupled devices (CCD) have been commercially successful and their size has reached four million pixels. As their cell size has become smaller, however, the number of stored electrons has decreased and the image quality has been degraded. There is a trade-off relation between resolution and image quality. Kiuchi *et al.*[1,2] therefore developed a method to improve resolution of an image sensor by using digital signal processing and optical low-pass and band-pass filters with ideal properties. Because their method was applicable only to one-dimensional imaging, we have extended it to two-dimensional imaging.[3,4]

In this work, resolution progress using digital signal processing and optical low-pass filters is proposed. First the principle of resolution progress of a two-dimensional image with optical low-pass filters used for such as a digital still camera was considered. Program for digital signal processing was developed based on this method. The program consisted of a discrete Fourier transform (DFT), complex linear equation calculator and an inverse DFT (IDFT). Using this program, progress of resolution was performed.

II. Enhancing the resolution of one-dimensional images

The principle of the method as applied to a one-dimensional image is shown in Fig. 1. An image that has frequency components up to the sampling frequency of the image sensor is taken by using an image sensor that either has or does not have an optical low-pass filter using crystal birefringence. As shown in Fig. 1(c), spatial frequency components of the input image that are higher than the Nyquist rate cause aliasing. And as shown in Fig. 1(d), two sampled images are translated to frequency domain components by using the discrete Fourier transform (DFT). The relationship between the frequency components before and after sampling is shown by the following equations.

$$S_1=S+S_a \qquad (1)$$
$$S_2=HS+H_aS_a \qquad (2)$$

where

- S_1 is the frequency component after sampling without optical processing
- S_2 is the frequency component after sampling with optical processing (low-pass filtering)
- S and S_a are the frequency components before sampling
- H and H_a are transfer functions of the low-pass filter

These equations can be used to calculate the original frequency components, S and S_a, from S_1, S_2, H, and H_a (Fig. 1(d)). Calculated frequency components are set to original frequency, and the image including frequency components higher than the Nyquist rate of the image sensor is reconstructed by using the inverse DFT (IDFT) (Fig. 1(e)).

III. Enhancing the resolution of two-dimensional images

This principle can be extended to two-dimensional images. Equation (3) shows the relation between the original signal and its replicants.

$$C'_{mn} = \sum_{m+tP=-\infty}^{\infty} \sum_{n+uQ=-\infty}^{\infty} C_{m+tP,\,n+uQ} \qquad (3)$$

The quantities t and u are natural numbers, C'_{mn} is the Fourier coefficient, and P and Q are respectively the numbers of pixels horizontally and vertically. This equation is the two-dimensional Nyquist theorem (sampling theorem) and, as shown in Fig. 2, can be used to calculate the relation between the original image and images with aliasing. Figure 2 shows frequency components of an original image. In this figure, the original image has the frequency components from $-f_{xs}$ to f_{xs} in the horizontal direction and frequency components from $-f_{ys}$ to f_{ys} in the vertical direction. This image is sampled at f_{xs} and f_{ys}, and areas B_x, C_x, and D_x cause aliasing in area A_x.

If the image shown in Fig. 2(a) is sampled at f_{xn} and f_{yn} through four different filters, the relationships between frequency components a_1, b_1, c_1, and d_1 are shown as follows:

$$a_1' = h_{11}a_1+h_{12}b_1+h_{13}c_1+h_{14}d_1 \quad (4)$$
$$a_1'' = h_{21}a_1+h_{22}b_1+h_{23}c_1+h_{24}d_1 \quad (5)$$
$$a_1''' = h_{31}a_1+h_{32}b_1+h_{33}c_1+h_{34}d_1 \quad (6)$$
$$a_1'''' = h_{41}a_1+h_{42}b_1+h_{43}c_1+h_{44}d_1 \quad (7)$$

The terms a_1'-a_1'''' are the frequency components of a_1 after sampling and can be calculated by using the DFT of the images produced by the image sensor. And h_{11}-h_{44} are the transfer functions of the optical filters and can be calculated from the properties of optical low-pass filters. These equations can be used to calculate the original frequency components a_1, b_1, c_1, and d_1 can be calculated from a_1'-a_1'''' and h_{11}-h_{44}. Analogous equations can also be used to calculate the frequency components a_2-d_2, a_3-d_3, and a_4-d_4. Finally, reconstructed frequency components are translated to the image with frequency components higher than the Nyquist frequency by using the IDFT.

IV. Results and Discussion

Experiments were performed using an 80-kilopixel (320x240 pixels) monochrome CCD image sensor and optical low-pass filters using crystal birefringence. Only part of the image (192x192 pixels) was used. The transfer function of the optical filter was assumed to be that of a 4th-order averaging filter. The input image was that of either a CZP (Circular Zone Plate) chart or an ITE (the institute of image information and television engineers in Japan) resolution test chart. Edge of the image was decided to the sampling rate of the CCD image sensor, that is, the input image includes frequency components twice as high as Nyquist frequency.

Images of the CZP chart before and after the processing are shown in Fig. 3. Aliasing can be observed in the original image, but the reconstructed image includes frequency components higher than the Nyquist frequency of the image sensor. Frequency components generated by aliasing are transferred to original frequency higher than the Nyquist frequency.

Figures 4(a) and 4(b) show the images of an ITE resolution test chart before and after processing. In the input image, 220 lines are distinguished; in the reconstructed image, 310 lines are distinguished. The resolution is increased by 40% but noise can be seen. This noise is mainly due to the positional shifts of the four input images. These shifts will be corrected by signal processing, but its accuracy must be improved.

Conclusions

The resolution of a CCD image sensor can be increased more than 40% by using optical low-pass filters and digital signal processing. This means that high-resolution images that have spatial frequencies beyond the Nyquist frequency can be obtained from conventional low-resolution CCD image sensors. Noise in the reconstructed image is caused by the positional shifts of the four input images, however, and must be reduced by increasing the accuracy with which these shifts are corrected.

References:

1) Y. Kiuchi, T. Sakusabe and S. Saruya ; ITE Technical report Vol. 18, No.67, (1994) pp. 1-6. (in Japanese)
2) Y. Kiuchi and T. Sakusabe ; 1995 ITE Annual Convention, pp. 59-60 (in Japanese)
3) T. Kimura et al. ; 1999 IEEE Workshop on CCDs and AIS, (1999) pp. 118-121.
4) T. Kimura et al. ; Trans. IEE of Japan Vol. 120-E, No. 8/9, (2000) pp. 410-416 (in Japanese)

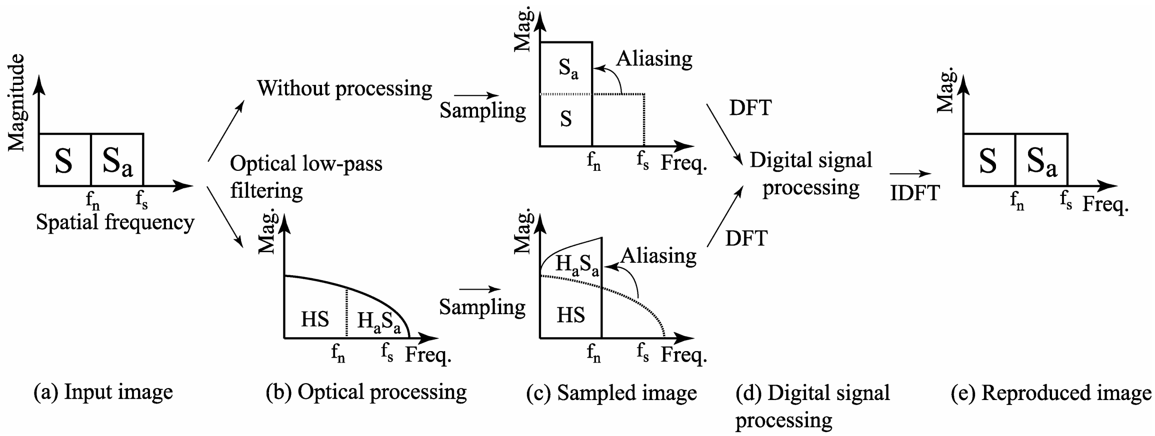


Fig. 1. Principle of resolution enhancement for image sensors with and without an optical low-pass filter. Only the case of a one-dimensional image is shown here.

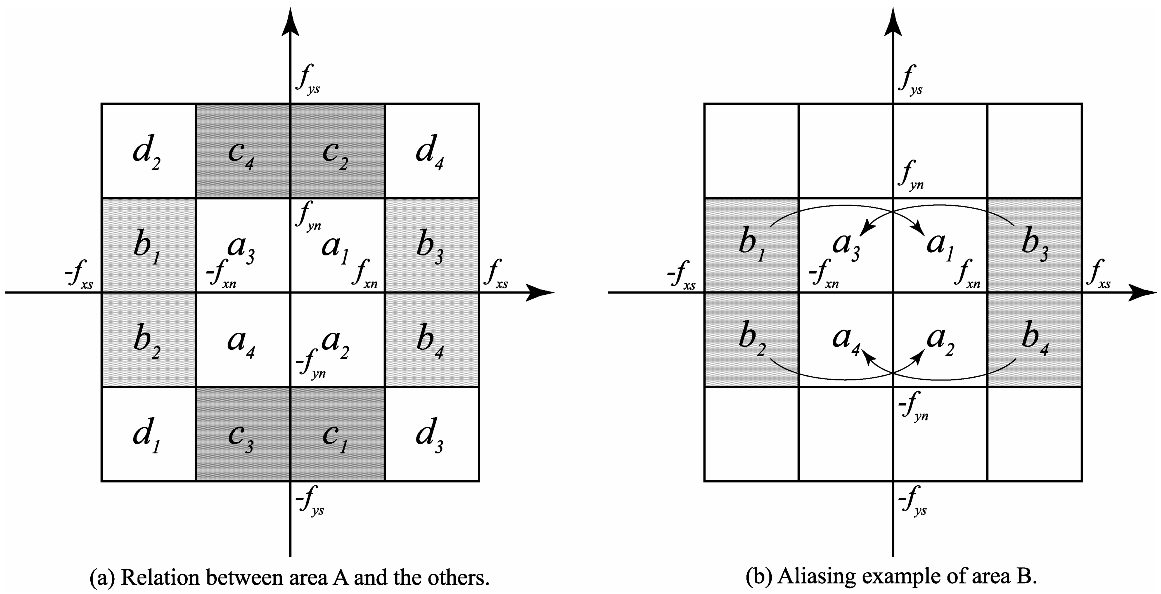
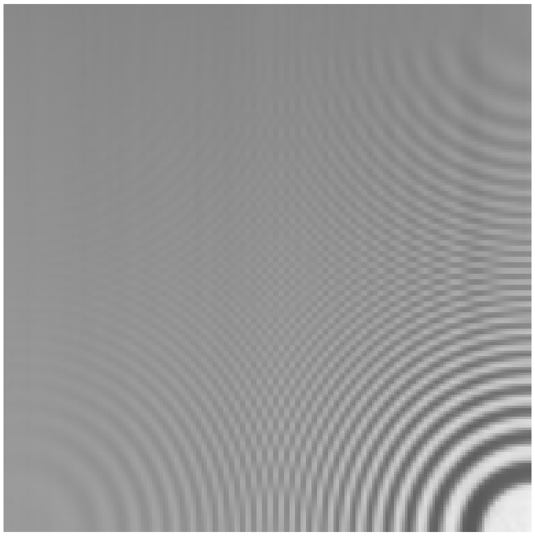
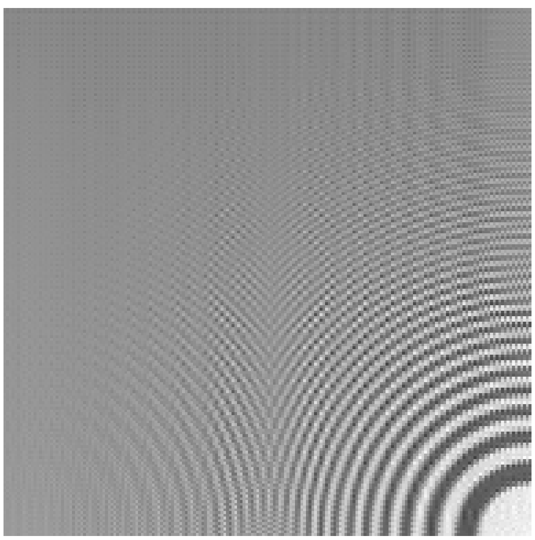


Fig. 2. : Relation between the original and replicant images. Areas *B*, *C*, and *D* with the same subscript number cause aliasing in the corresponding area *A*.

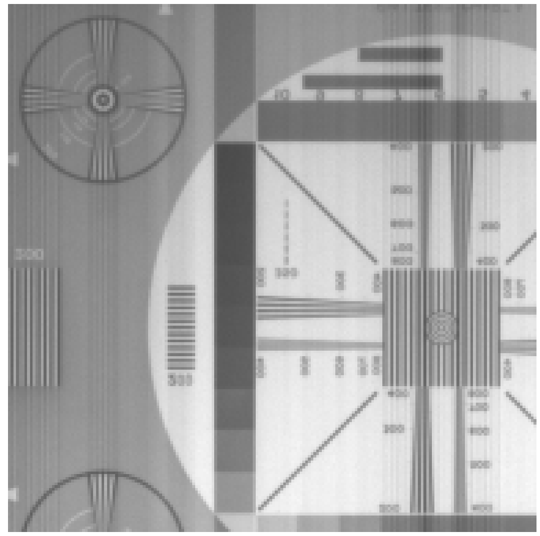


(a)

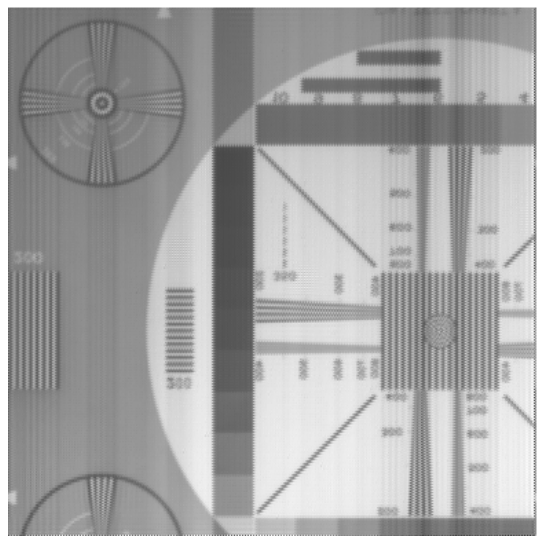


(b)

Fig. 3. Original and reconstructed images of a quarter of a CZP test chart: (a) 192x192-pixel input image, (b) 384x384-pixel reconstructed image. For comparison with the reconstructed image, the original image shown here is magnified by a factor of two. Aliasing is found in the input image.



(a)



(b)

Fig. 4. Original and reconstructed images of an ITE resolution test chart: (a) input image, (b) reconstructed image. In the input image are distinguished 220 lines, and in the reconstructed image are distinguished 310 lines.