Paper

An Improved Image Reconstruction Method for a Chopperless Pyroelectric Infrared Image Sensor

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This paper presents an improved method of image reconstruction from the chopperless pyroelectric infrared image sensors. In the chopperless image sensor using chip shift operation, the output is a spatially differentiated image. The original IR light image can be reconstructed from the sensor output using the spatial integration. The improved method uses the chip shift operations to both x and y direction to cancel the stripe shape noise. This technique much improves the quality of the reconstructed image.

Keywords: Infrared imager, Chopperless, Image reconstruction, Chip shift imaging

1. Introduction

Uncooled infrared (IR) image sensors are increasingly demanded for many applications such as security systems. An infrared image sensor using pyroelectric material has the highest sensitivity in thermal type infrared imagers. Since the output signal of the pyroelectric type infrared detector responds to the variation of the infrared light, a mechanical light-chopping system is necessary. Use of such a mechanical device restricts the application area of the highly sensitive pyroelectric type image sensors. The authors have presented a new concept of highly sensitive infrared image sensors: a chopperless CMOS-based pyroelectric infrared image sensor [1]. Instead of using the mechanical chopper, the proposed scheme uses a simple piezoelectric actuator to shift the sensor and a signal processing technique to estimate the original IR light image. The IR camera system using the small light actuator has a distinct advantage over the systems with the mechanical choppers. The chip shift operation with the piezoelectric actuator is often used for CCD visible image sensor to enhance the resolution [2]. Furthermore, the piezoelectric actuators are also used for the precise control of imaging systems such as AFM and STM. Therefore, the reliability and the accuracy of the piezoelectric actuator are sufficient for our purpose.

The pyroelectric sensor output with chip shift operation is a spatially differentiated image. Therefore, using spatial integration, the original IR light image can be estimated. However, the image quality is not good enough for the case of the one-dimensional chip shift operation. Stripe shape noise is superimposed in the reconstructed image. In this paper, a method to obtain an improved reconstructed image using two-dimensional chip shift operation. The stripe-shape noise is successfully canceled with both the vertical and horizontal chip shifts, leading to the improved quality of the reconstructed image. In the following, the principle and the results of image reconstructions are described.

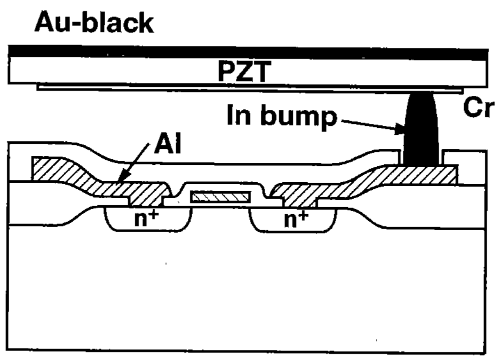

Fig. 1. Conceptual view of the CMOS IR image sensor (pixel structure).

2. Structure and Principle

2.1 Chopperless CMOS IR sensor The conceptual view of the CMOS-based infrared image sensor is shown in Fig. 1. A pyroelectric thin plate (PZT) is put onto the CMOS readout chip and is connected electrically through indium bump. An mechanical light-chopper to give the temperature variation in the pyroelectric type infrared image sensor is replaced by an piezoelectric actuator as shown in Fig. 2. The actuator shifts the sensor chip to vertical or horizontal direction of the focal plane. As a result of the chip shift operation, the image captured by the sensor chip is a spatially differentiated one. The original image whose intensity is proportional to the IR light energy can be reconstructed with the spatial integration.

2.2 CMOS IR image sensor The block diagram of the IR image sensor system is shown in Fig. 3. The system consists of IR image array, S/H array at the column, A/D converter (ADC), frame memory with a digital subtracter, and a DSP(digital signal processor) for image reconstruction.

Figure 4 shows the pixel circuit for the chopperless IR sensor. The conventional pyroeletric IR pixel circuits often use a source follower buffer [4] or passive pixel technique [5]. The pixel circuits with a reset transistor are called active pixels and are often used for visible CMOS image sensors [3]. The active pixel circuits are also useful for the pyroelectric IR image sensors. The operation is shown in Fig. 5. The terminal voltage (V_s) of the pyroelectric detector is periodically reset for the fixed pattern noise cancellation of the pixel circuits. For the constant IR light illumination (dashed line), V_s behaves as dashed line. This is because of the discharging due to the parallel resistance of the pyroelectric detector. In the case that infrared light intensity is periodically changed due to the chip shift operation, the terminal voltage V_s behaves as the solid line. This is because of the charge variation(Q_s) due to the spontaneous polarization of the pyroelectric detectors. To read out the signal voltage V_s at the output of image array, a MOS transistor switch MS is turned on, and then a MOS transistor MIN and a MOS transistor for the current source at the output constitutes a source follower buffer circuits. Therefore, the output follows the signal voltage V_s. The source follower has ideally the gain of unity and a d.c. voltage level is shifted. This d.c. level shift contains the threshold variation of MIN, which results in fixed pattern noise. To cancel the fixed pattern noise and to extract the signal component due to the variation of spontaneous polarization of the pyroelectric detectors, two levels of V_s are read out. The first level is sampled by READ1 pulse in the lower illuminance level of IR light, and is held at the S/H circuit array at the column.

By taking the difference of the readout signals sampled by READ1 and READ2 pulses, the signal component proportional to the difference of the two IR light levels is extracted. To do this, the signal sampled by READ1 pulse is converted to digital by the ADC and memorized in a frame memory. The difference of the signal sampled by READ2 pulse from the memorized signal is taken by the digital subtracter. The noise cancelled signal is given to the DSP for image reconstruction.

2.3 principle of image reconstruction The principle of the estimation of the original image from the output of the pyroelectric imager is as follows. Figure 6(a) shows a 1-dimentional model of the movement of image. A sensor pixel at the location x is moved to

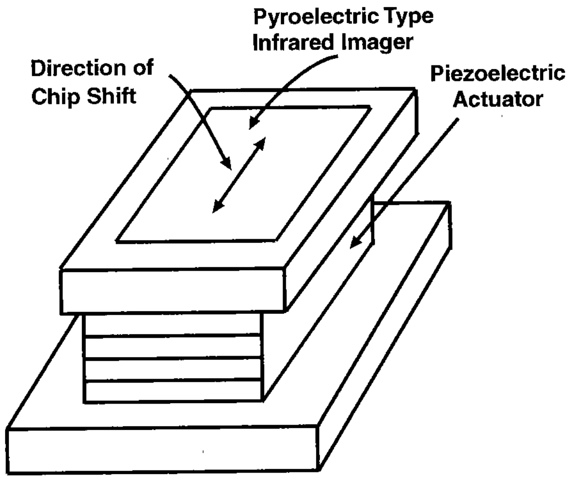

Fig. 2. Sensor chip shifting using piezoelectric actuator.

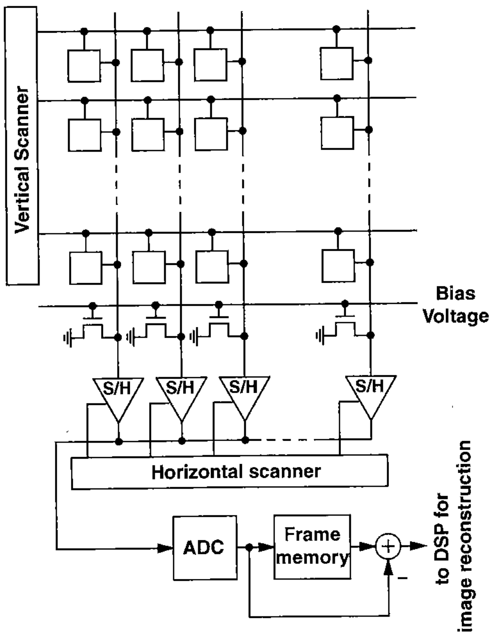

Fig. 3. Block diagram of the CMOS IR image sensor system.

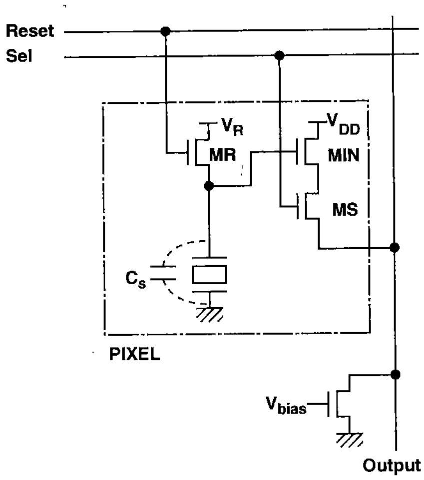

Fig. 4. Active pixel circuit for the IR sensor with the chip shift operation.

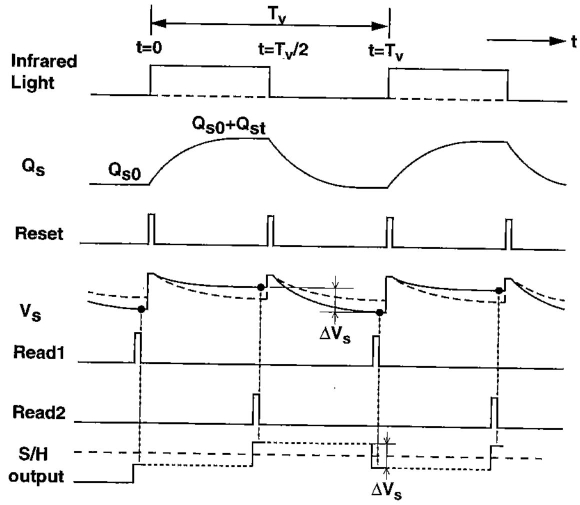

Fig. 5. Operation of the IR active pixel sensor circuit.

$x+\Delta x$, and at t_0 the signal charge is detected. Since the pyroelectric detector responds to the time variation of the infrared light, the sensor output $S(x,t_0)$ at location x at time t_0 can be modeled as

$$S(x,t_0) = A(E(x,t_0-\tau) - E(x,t_0)) \cdots\cdots\cdots (1)$$

where A is the gain factor of the sensor and τ the time difference of the chip shift operation. Obviously from Fig. 6, the response is equivalent to the spatial variation of the infrared light between x and $x+\Delta x$. Namely,

$$S(x,t_0) \simeq A(E(x+\Delta x,t_0) - E(x,t_0)), \cdots\cdots (2)$$

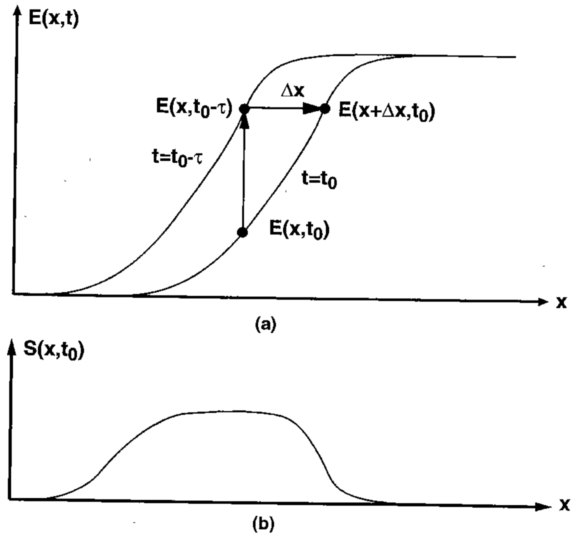

Fig. 6. One-dimensional model for the chip shift image and the sensor output.

If the spatial variation is linear between x and $x+\Delta x$,

$$S(x,t_0) \simeq A\Delta x \frac{d}{dx} E(x,t_0) \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Therefore, the original image $E(x,t_0)$ can be estimated by integrating the sensor output if we know the boundary value of image, $E(0,t_0)$ as

$$E(x,t_0) = E(0,t_0) + \frac{1}{A\Delta x}\int_0^x S(\xi,t_0)d\xi \cdots\cdots (4)$$

In the actual image reconstruction process, the gain and the offset are given to the spatially integrated data to fit the gray scale using the histogram as shown in Fig. 7. From the histogram of the spatially integrated data E, the minimum (e_{min}) and the maximum (e_{max}) values are obtained. To fit it to the N_g-level gray scale image, the following linear mapping is carried out.

$$P = [G \times E] + N_g/2 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where

$$G = \frac{N_g}{e_{max} - e_{min}} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

is the gain of the mapping, and $[a]$ denotes the smallest integer such that $[a] \geq a$.

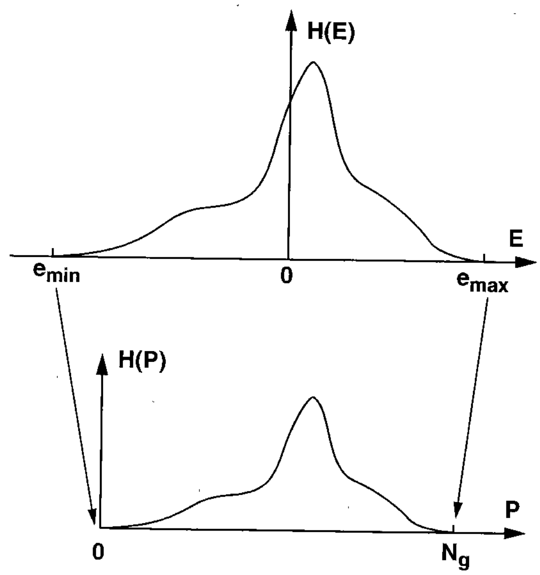

Fig. 7. Mapping to N_g-level gray scale using the histogram.

3. Image reconstruction

3.1 Generation of the pseudo sensor output image In order to confirm the reconstruction of the original IR light image from the chip-shifted pyroelectric sensor output, simulations are conducted using pseudo sensor output images. Figure 8 shows a picture used for the simulations. The pseudo sensor output image is generated by taking the difference of the 1-pixel shifted picture from the original picture as shown in Fig. 9.

3.2 1-D chip shifting and integration The reconstructed images are shown in Fig. 10 and Fig. 11 for the vertical chip shifting and the horizontal chip shifting, respectively. These reconstructed images are obtained by the integration and the mapping to a 256-level gray scale. Although the degradation of the image

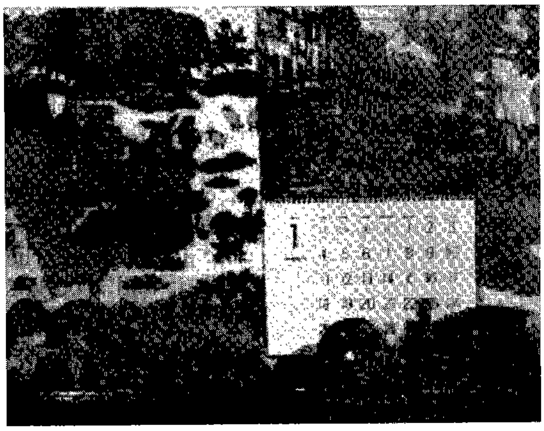

Fig. 8. Original image used for the simulations.

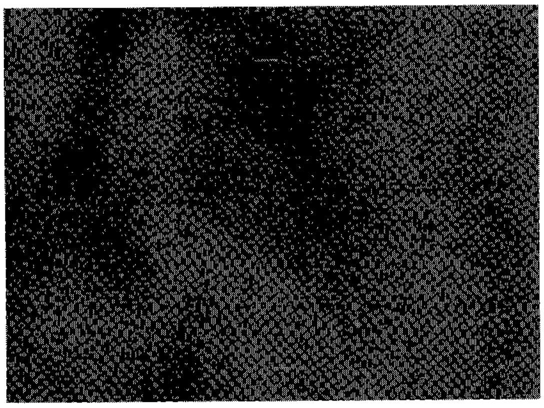

Fig. 9. Pseudo sensor output image.

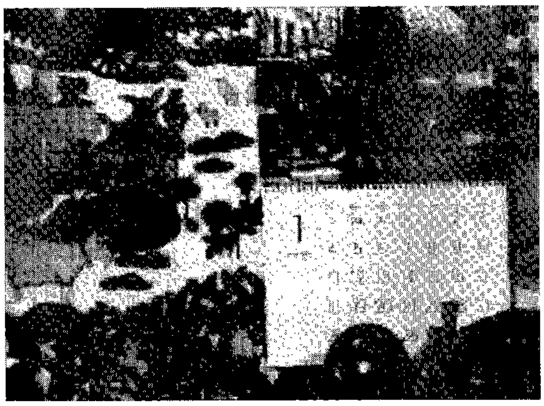

Fig. 10. Reconstructed image for vertical chip shifting.

quality is occurred, it is shown that the original image information can be estimated from the pyroelectric infrared image sensor without any chopper, but with moving the sensor. The reconstructed images with the vertical and the horizontal chip shiftings contains the vertical and the horizontal stripe shape noises, respectively.

The reason of the degradation of the image is because the DC component of the original image cannot be estimated. In the process of spatial integration, $E(0, t_0)$ in Eq. (4) for each line of pixels is assumed to be the same. However this is not always true. The improper assumption causes the stripe shape noise in the image.

The transfer function due to the chip shifting depends on the magnitude of shifting. If the shifting of the chip is exactly the length of a pixel, the transfer function and the frequency response are given by $H(z) = 1 - z^{-1}$ and $|H(e^{j\omega P})| = |2\sin(\omega P/2)|$, respectively, where P is the pixel pitch. Therefore, the frequency response of differentiation is compensated by the spatial integration for the reconstruction whose frequency response is approximately given by $|1/2sin(\omega P/2)|$. However, the control of the magnitude of shifting to be exactly the pixel pitch is not so easy. A reconstructed image in the case that the magnitude of shifting is the length of 5 pixels is shown in Fig. 12. In this case, the frequency response of the chip shifting is given by $|2\sin(\omega 5P/2)|$. The total frequency response in the reconstructed image, $|\sin(\omega 5P/2)/\sin(\omega P/2)|$ results in spatial low-pass filtering in the image as shown in Fig. 12. However the degradation of image quality is not so drastic. In our simulation, the mismatch of less than three pixels in the chip shifting magnitude does not cause crucial degradation of the reconstructed image.

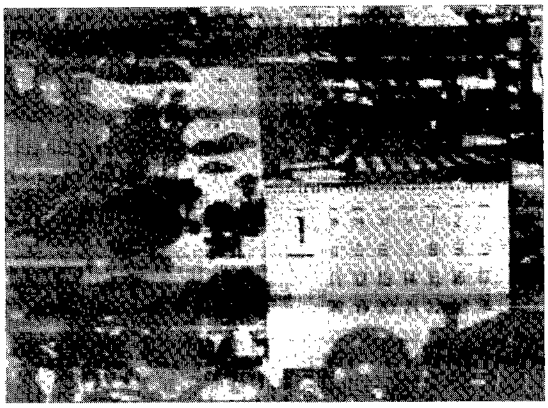

Fig. 11. Reconstructed image for horizontal chip shifting.

3.3 Reconstruction with 2-D chip shifting

If we can swing the sensor both in x and y directions, the estimated image quality can be improved. The principle is shown in Fig. 13. First, the sensor is shifted to x(vertical) direction and the original image is estimated by the spatial integration to y direction. As a result of this estimation, the reconstructed image contains vertical stripe shape noise. Similarly the sensor is shifted to x(horizontal) direction and the original image is estimated. In this case, the reconstructed image has stripe noise in x direction. The reconstructed pixel value at the location (i,j) for shifting x and y directions are assumed to be $E_x(i,j)$ and $E_y(i,j), (i=0,...,N-1), (j=0,...,M-1)$, respectively. The first step is to calculate the projected 1-dimensional data to y-direction for both the reconstructed images of x and y shift operations. The projection of these reconstructed data to y direction is calculated as

$$P_x(i) = \sum_{j=0}^{M-1} E_x(i,j) \cdots\cdots\cdots (7)$$

$$P_y(i) = \sum_{j=0}^{M-1} E_y(i,j) \cdots\cdots\cdots (8)$$

In the case of the y-direction shift image, the projected data contains the stripe shape noise distribution in addition to the distribution of the original image. On the other hand, in the case of the x-direction shift image, the stripe shape noise only affects to the offset in the projected data in addition to the distribution due to the original image. Therefore, by taking the difference between two projected data, $D(i)$ as

$$D(i) = P_y(i) - P_x(i), \cdots\cdots\cdots (9)$$

we can estimate the stripe shape noise distribution.

The final step is to subtract the estimated stripe shape noise from the reconstructed image using y-direction shift operation. Since the projected data contains the accumulation of the stripe shape noise, the amplitude of the noise is divided by the number of vertical number of pixels, M. Therefore, the noise cancelled output $C(i,j)$ is given by

$$C(i,j) = E_y(i,j) - D(i)/M + C_0 \cdots\cdots\cdots (10)$$

where C_0 is an offset to adjust the total brightness of image. In this way, the stripe shape noise is greatly reduced. Figure 14 shows the reconstructed image using the noise cancellation technique. The image quality is much improved compared with Fig. 10 and Fig. 11.

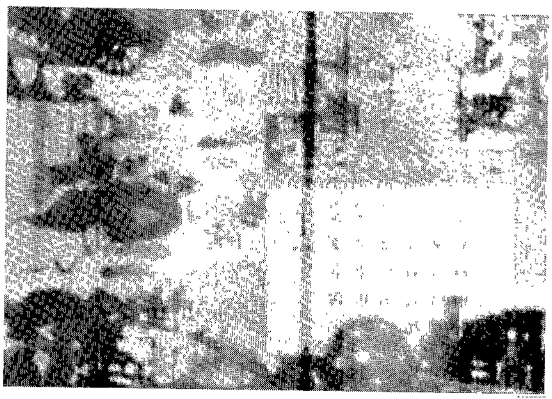

Fig. 12. Reconstructed image for the chip shifting of 5 pixels.

3.4 Discussion There is a limitation for the application of the proposed method. The speed of the motion of scene have to be small enough compared with that of the chip shift operation. Otherwise, the distortion in the reconstructed image becomes serious.

The speed of chip shifting is limited by either the responsivity of the piezoelectric actuator or the thermal response of the pyroelectric detectors. In the piezoelectric actuator, the maximum chip shift operation frequency is limited by the resonance frequency of the actuator. A typical piezoelectric actuator has the resonance frequency of about a 200 Hz and 2000Hz for the magnitude of shifting of $100\mu m$ and $10\ \mu m$, respectively. When we implement a high-resolution IR image array with the pixel size of around $10\ \mu m \times 10\mu m$, the speed of the actuator does not become the limiting factor of the chip shift operation. The thermal responsivity depends on the goodness of the thermal isolation of the pyroelectric detector. The silicon micro-machining technology is improving the responsivity of the thermal-type IR imager. However we have to wait the development of a structure for good thermal responsivity in order to use the proposed technique at the video rate.

Recent applications of IR image sensors is widely expanding. The proposed technique may not be suitable for applications which require high-speed image capturing such as intelligent transportation systems (ITS). A possible application is a personal IR camera for portable use since both the high sensitivity and the portability are required. Such an IR camera may be useful for walking in the dark.

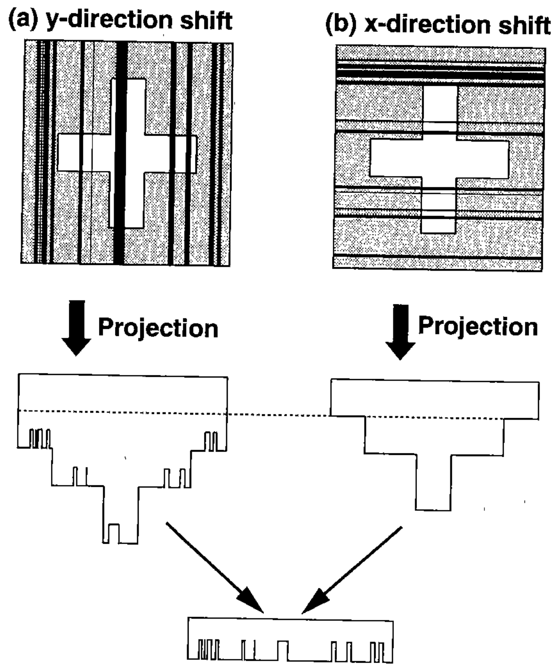

Fig. 13. Reconstructed image for horizontal chip shifting.

4. Conclusions

This paper has presented a chopperless pyroelectric

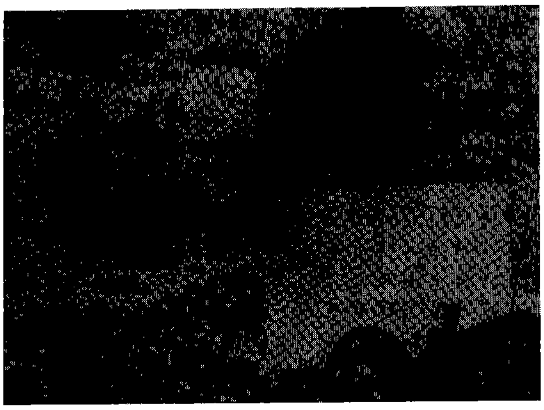

Fig. 14. Improved reconstructed image.

type infrared image sensor. The original image can be reconstructed by the spatial integration of the pyroelectric sensor output with chip shift operation. The two-dimensional chip shift operation and the corresponding image reconstruction technique improves the quality of the reconstructed image. The demonstration through the prototype chip implementation is left as near future subject.

(Manuscript received July 9, 2001, revised October 25, 2001)

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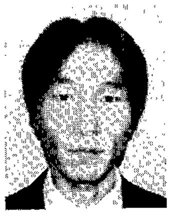

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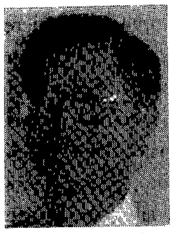

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