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Bimodal fingerprint capturing system based on compound-eye imaging module

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A compact imaging system called TOMBO (Thin Observation Module by Bound Optics) is proposed in which a microlens array is used for thin hardware configuration. This paper describes a fingerprint-capturing module as an application of the TOMBO. Experimental results by the TOMBO prototype system are shown to clarify the applicability of the TOMBO to the fingerprint capturing. Different types of biometrics, i.e., fingerprint and face images, are captured by the same hardware, which shows the extendability of the system for multimodal identification. © 2004 Optical Society of America

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1. Introduction
In recent years, authentication has been an important issue for the realization of various services over the Internet, such as electronic commerce or electronic government. Biometrics techniques using the information of a living body like a fingerprint or an iris are promising, because they can improve security strength as compared with conventional methods using a password or a personal identification number. One application of the authentication is found in electronic commerce using a personal digital assistant, such as a cellular phone. In such a system, the identification of the legal user is crucial to the security of the system. For this purpose, a personal digital assistance device with the functionality of authentication is considered to be as effective. Among various biometrics, fingerprint identification has been studied actively owing to its convenient usage and effective performance. A key issue of the fingerprint identification is how to obtain fingerprint data so that various types of fingerprint sensors using optical imaging or electric capacitive distribution are investigated. The TOMBO (Thin Observation Module by Bound Optics) system, a compound-eye imaging system proposed by the authors, is attractive for the fingerprint sensor because of its thin hardware configuration. However, the TOMBO system was originally designed to capture the image of an object located at a distant position. Therefore, by modification of the optical system, we adapt the TOMBO system to capture the image of an object at a near position.

In this paper, an application of the TOMBO system to fingerprint capturing is presented. In Section 2 the principle of fingerprint capturing based on the TOMBO system is explained. In Section 3 an experimental result by the TOMBO prototype system is described. In Section 4 bimodal image capturing, in which fingerprint and face images are captured by the same hardware, is demonstrated as an interesting extension of the TOMBO system. The result provides a notable feature of the TOMBO architecture, which is expected to be useful for multimodal authentication.

2. Fingerprint Capturing by Use of the TOMBO
A fundamental configuration of the TOMBO is shown in Fig. 1. The TOMBO is composed of a microlens array, a signal separator, and a photodetector array. A signal separator prevents optical signal cross talk between the adjacent lenses. The TOMBO provides small and lightweight hardware through miniaturization of the lenses. Usually, miniaturization of the optical system causes a reduction of the image resolution. However, in the TOMBO system, signal processing retrieves a high-resolution image using
multiple low-resolution images captured by compact imaging systems. When the low-resolution images have different sampling information, they can be utilized for the image reconstruction. For use as the reconstruction method, the image-sampling method, the backprojection method, and the pixel-rearrangement method were proposed. The experimental results by use of the TOMBO prototype system show the effectiveness of the pixel-rearrangement method.

The finger-prints capturing system based on the TOMBO is composed of the same elements as the conventional TOMBO system, except for the illumination components. The original TOMBO system is set to focus on infinity or a near-infinity point. On the other hand, the proposed TOMBO system for fingerprint capturing is set to focus on the surface of the light-guide plate.

Figure 2 shows a setup of the fingerprint-capturing module. An elemental imaging system corresponding to a microlens is called a unit. An image captured by a unit is called a unit image. A set of unit images captured by the entire system is called a compound image. In the original TOMBO system, all the units observe almost the same part of the target at a time. On the other hand, the proposed system observes a different part on a unit-by-unit basis. The captured compound image is a set of rotated images captured by each unit. The wall of the signal separator obstructs the incident light, so that the edge of the unit image becomes dark. Therefore the magnification ratio of the optical system is set as less than unity in order to not lose the information of the fingerprint. The magnification ratio of the optical system \( m \) for the maximum resolution of the fingerprint image is provided by

\[
m = 1 - \frac{2p}{l} \left\lfloor \frac{w}{2p} \right\rfloor,
\]

where \( l, w, \) and \( p \) are the lens pitch, the thickness of the separation wall, and the pixel pitch of the imaging sensor, respectively. \( \lfloor \cdot \rfloor \) means a roundup operation below the decimal point.

Instead of the reconstruction methods developed for the TOMBO system, the following procedure is adopted to achieve simple and fast reconstruction.

1. Shading compensation and fixed pattern noise reduction.
2. Separation of the unit images.
3. Removal of the edge pixels in the unit image.
4. Rotation of the clipped unit image.
5. Combination of the all rotated images.
6. Gray level correction.

For the preprocessing, the shading and the fixed pattern noise are compensated with a white reference image and the background image. The captured compound image is divided into the unit images. Based on the magnification ratio of the optical system, the edge pixels in the unit image are removed. The clipped unit image is rotated 180°, and all of the processed images are combined. The gray level of the resulting image is corrected to enlarge the dynamic range. Finally a segment image of the fingerprint is obtained.

The field-view size of the fingerprint is limited by the chip area of the image sensor. However, this is a simple restriction of available chip, and a large area chip can enlarge the field view with an increase of the fabrication cost. Another option is to tile multiple small sensors for emulation of a large sensor. Instead, we use a novel method in which multiple fingerprint images at different points are captured by moving the finger on the sensor. All of the segment images are combined to reconstruct a large area of the fingerprint. The relative distance between the two images is calculated by the pattern-matching method. If sequential detection is introduced, not only the shape of the fingerprint but also the action of the finger can be detected by the same sensor.

The image combining is achieved by the following procedure. The target fingerprint is assumed to be moved relative to the sensor, and a sequence of the segment images of the fingerprint is captured. Let \( f(x, y) \) and \( g(x, y) \) be two successive segment images through movement of the finger, each of which is reconstructed from the captured data. The distance between the two segment images is estimated by the pattern matching method. The sequential similar-
It is difficult to measure exact microlens–photodetector distance because of the difficulty in determining the principal points of the microlenses. Therefore we presumably set the object–microlens distance and the trimming size as 32 × 32 pixels for reconstruction. In this case, the object distance and the magnification ratio of the system are 5.46 mm and 0.64, respectively. Then we adjust the microlens–photodetector distance to obtain a smooth connection over the reconstructed image. The optimum position is decided by visual inspection.

B. Experimental Results

The captured image by the experimental TOMBO system is shown in Fig. 3. The image size is 500 × 500 pixels. The captured image is compensated with respects to the shading and the fixed pattern noise by use of the reference images captured previously.

The reconstructed fingerprint image with the trimming size of 32 × 32 pixels is shown in Fig. 4. The image size is 320 × 320 pixels. The observation area is 5 × 5 mm², which is determined by the lens pitch and the number of units. The resolution of the fingerprint image is 1727.2 dots per inch (dpi).

The four pieces of the segment images are captured by changing the observation position of the target. The moved distance between the segment images are estimated, and these values are used to connect them as shown in Fig. 5. As seen from the figure, each segment image is combined correctly, and the reconstructed image of 12.8 × 5.0 mm² is retrieved.

![Fig. 3. Captured images.](image-url)
4. Discussion

The thickness of the system depends mainly on the focal length of the microlens and the magnification ratio of the optical system. The magnification ratio of the optical system \( m \) is determined by

\[
m = \frac{2p}{l} \left[ \frac{l r}{50.8 \times 10^3} \right],
\]

where the required resolution of the fingerprint image, the lens pitch, and the pixel pitch are \( r \) dpi, \( l \) \( \mu \)m, and \( p \) \( \mu \)m, respectively.

Figure 6 shows the calculation result of the relationship between the object distance and the resolution of the fingerprint image when the lens pitch, the focal length, and the pixel pitch are \( 500 \) \( \mu \)m, \( 1.3 \) mm, and \( 10 \) \( \mu \)m, respectively. The resolution for scanning a fingerprint is typically \( 500 \) dpi, so the object distance of the system should be set near \( 6–8 \) mm.

The proposed system can capture a high-resolution fingerprint image. On the other hand, if the magnification ratio is set small and if the lens–photodetector distance is close to the focal length of the lens, the same hardware can capture an object located at a distant position as well as an object on the surface of the lens. For example, we can capture both the fingerprint and the face images with the same hardware. However, with the original configuration for the fingerprint capturing, the captured image of the face is remarkably out of focus. A solution of this problem, a focus adjustment mechanism that uses a microactuator such as a piezoelectric actuator, can be considered. However, the compactness of the TOMBO system is greatly reduced by the mechanism. Therefore as another solution we design an optical system balancing the defocus of the both imaging modes.

The same specifications of the microlens as used in the experimental system are assumed. The required resolution of the fingerprint image is set as \( 500 \) dpi. The trimming size is set to \( 10 \times 10 \) pixels from the resolution. The amount of the defocus is set to the distance where both the diameter of the blur circle in the face image and the fingerprint image-capturing mode are almost equal. The diameter of blur circle \( \delta \) for the face image-capturing mode is provided by

\[
\delta = \frac{b}{a} - \epsilon,
\]

where \( a \), \( b \), and \( \epsilon \) are the lens–photodetector distance, the diameter of the element lens, and the amount of defocus, respectively. In the same way, the diame-
The speed and the direction of the finger movement is also detected through sequential analysis of the segment images. Therefore a series of finger movements can be used as a personal identification key. In addition, finger action is utilized as an input method for a device with authentication capability.

5. Summary

A thin fingerprint-capturing module using the compound-eye imaging system TOMBO has been proposed. A simple and high-speed reconstruction method for the fingerprint capturing has been described. A fingerprint image of 1727.2 dpi was captured by the experimental system. The experimental result proved the capability of capturing a fingerprint image by the proposed method. A large area of an image can be successfully reconstructed by a combination of multiple segment fingerprint images with the pattern-matching method. As a notable feature of this system, fingerprint and face images can be captured with the same hardware. With these functionalities, the proposed system is expected to be applied to a multimodal authentication system.

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