Optical design of high performance fingerprint scanner with large capture size

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We present an optical design for a fingerprint scanner that addresses the challenges involved in capturing the prints of rolling fingers. A rolling fingerprint scanner requires a high performance distortion free system with big object space numerical aperture (0.022) and larger capture size (40 × 40 (mm)). We show how these requirements can be achieved with the approach of optical and computational hybrid distortion correction. In addition, dark background illumination is utilized to increase fingerprint contrast.

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Biometric technology is becoming the foundation of highly secure identification and personal verification solutions. Due to reliability concerns, fingerprint identification has obtained the highest market share among the different methods of biometric identification. It has been extensively used in many commercial and government applications, including criminal investigation.

The optical fingerprint scanner commonly uses a prism as a capture component, especially when large capture size is needed. Distortion correction and fingerprint resolution are two basic requirements in an optical fingerprint scanner.

The optical fingerprint scanner usually comprises of the capture prism and imaging lens. One issue inherent in this arrangement is that the capture surface in the prism is not perpendicular to the optical axis, which results in trapezoid distortion in the image plane. This distortion needs to be corrected before the identification process[1−4]. Optical designers have created different solutions employing anamorphic optics to reduce or correct trapezoid distortion. For example, Han invented a compound prism method for this purpose[5]. Lin *et al*. presented a method of using asymmetrical aspheric lens to reduce distortion and improve contrast[6]. Betensky invented an idea using cylinder lenses to correct the distortion[7]. However, because the remaining astigmatism introduced by anamorphic optics cannot be reduced to a small level, these systems cannot attain high performance while achieving big object space NA and large capture size at the same time. The general specifications of these solutions are shown in Table 1.

Fingerprint resolution is another basic constraint. For a commercial purpose, lower resolution is acceptable. But for criminal investigation, the standard resolution of a fingerprint scanner needs to attain 500 pixels per inch (ppi) in object space. This means the feature size of 0.0508 mm in the capture surface must be imaged larger than one pixel size of the sensor. In other words, the minimum magnification of the scanner is defined by the selection of the image sensor.

Table 1. General Specifications of Present Solutions

Solutions	Object Space NA	Capture Size or Height	$F/\#$
Compound Prism	0.0067	33×33 (mm)	12
Asymmetrical Aspheric Lens	0.021	9 mm	2.67
Cylinder Lenses	0.022	13.1 mm	5.1

Recently, the developments of technology and improvements of application have provided more critical challenges to fingerprint scanner design.

1) In order to detect fake fingerprints and develop new identification algorithms, the fingerprint scanner is required to improve performance in obtaining more detailed features such as sweat pores on the skin of the finger[8−11]. With respect to this demand, the object space NA of scanner should be large enough to increase resolution.

2) For a rolling fingerprint scanner applied in criminal investigation, the capture size has to be big enough to accommodate the rolling movement of the finger as the scanner captures the prints of the pad and sides of the fingertip. Better yet, it will be capable of capturing multiple fingers simultaneously.

3) With developments in the semiconductor industry, the pixel size of image sensors has become smaller and smaller. Correspondingly, the fingerprint scanner needs to reduce aberration to a small level and achieve high image space spatial resolution concomitant with high modulation transfer function (MTF) values.

In this letter, we focus on the optical design of a high performance rolling fingerprint scanner, and present a hybrid optical and computational distortion correction approach to meet the challenges mentioned above. We present in Table 2 the specifications satisfied by the design.

The optical system of a high performance fingerprint scanner should have the capability to distinguish small features and attain a high contrast fingerprint image.

Total internal reflection is usually proposed to increase the contrast in prism based fingerprint scanners. However, manipulating the way of illumination and treating the prism correctly will increase the contrast even more.

The conventional method of prism illumination and its test results are shown in Fig. 1, with the arrows in Fig. 1(b) indicating the cross section where the grey scale intensity data is taken and analyzed. When a finger presses on the prism, the ridges are in contact with the glass, so that light illuminating on the ridges will be scattered, while the light illuminating to the valleys will be total internal reflected because there is air between the valleys and the glass. The total internal reflected light is collected by the imaging lens. Consequently, the background of the fingerprint is bright. This method is so-called as bright background illumination.

Table 2. Specifications of Optical System for Rolling Fingerprint Scanner

Parameters	Value
Spectral Range of Illumination	630–680 nm, peak at 660 nm
Fingerprint Capture Size	40×40 (mm)
Object Space *NA*	0.022
Working *F* Number (*F*/#)	3.3
Magnification of Lens	–0.144
Pixel Size of CMOS Sensor	5.2×5.2 (μm)
Smallest Resolution in Objective Side	500 ppi
Distortion	$< 1\%$
Nominal MTF in Design	> 0.5

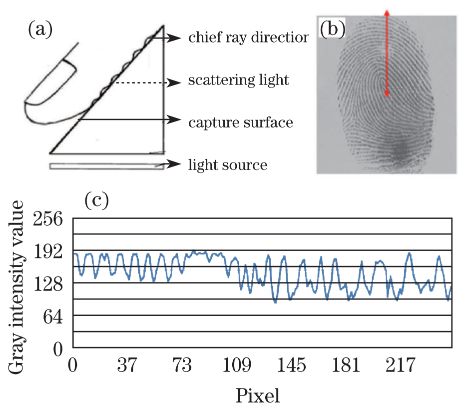

Fig. 1. Bright background illumination: (a) idea of illumination; (b) fingerprint image; (c) grey scale curves.

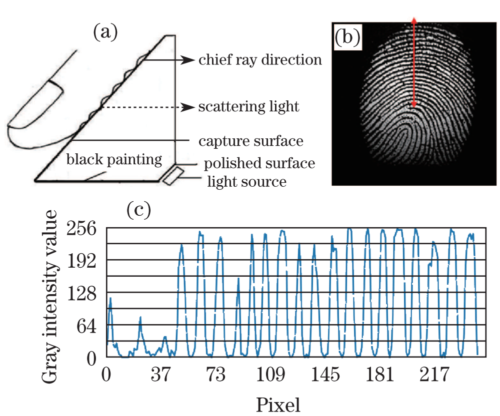

Fig. 2. Dark background illumination: (a) idea of illumination; (b) fingerprint image; (c) grey scale curves.

An improved method of prism treatment and its test results are shown in Fig. 2, with the arrows in Fig. 2(b) indicating the cross section where the grey scale intensity data is taken and analyzed. In this setup, the prism bottom is painted with absorption painting, and a surface parallel to the capture surface is polished to arrange the light source. When a finger presses on the capture surface, the light illuminating the ridges of finger is scattered. The light illuminating to the valleys is refracted through the capture surface. While the valleys work as a light trap for a percentage of the light, other portions of light scattered to the bottom of the prism is absorbed by the absorption painting, so that the optical system collects only the light in the chief ray direction of the lens within the angle defined by object space NA. In the area where there is no contact with the skin, the illumination light will transmit through the capture surface and the sensor receives no light from there, which means the background to the fingerprint contact area is dark. This method is so-called as dark background illumination.

As shown in Figs. 1 and 2, the contrast and the dynamic range of the fingerprint image in dark background illumination are noticeably improved. These improvements enable the fingerprint scanner to capture the prints of dry fingers more effectively.

For an optical distortion correction scanner, the remaining astigmatism introduced by anamorphic optics limits the performance of the machine and selection of image sensor (the pixel size need to be big) with respect to achieving large object space NA and capture size simultaneously. We conducted some simulations employing anamorphic optics for big capture sizes, and the results show that the astigmatisms cannot be reduced to a small level (for capture size 40×40 (mm), the remaining astigmatisms are all above 1 mm). A possible solution is to apply computer systems to correcting the trapezoid distortion but the electronic system would need to be very powerful to expedite the image processing. We realized that if the optical system could take care of partly correcting the distortion by attaining a rectangle image, the electronic system could be simplified and image processing time would be shortened. Based on this idea, we created the optical and computational hybrid distortion correction approach.

In this approach, we use double telecentric lens to obtain a rectangle image from a tilt square objective. With a double telecentric system, assuming a grid square is placed in the capture surface with the horizontal lines parallel to the arris of the prism, the magnification of points along the horizontal lines ($M_{\rm s}$) in sagittal direction is the same (as defined by the magnification of the lens). The magnification of points along the vertical lines ($M_{\rm t}$) in tangential direction is the same too, though smaller than the magnification in sagittal direction. The relationship between $M_{\rm s}$ and $M_{\rm t}$ is defined by

$$M_{\rm t} = \frac{\cos\theta}{\cos\theta'} M_{\rm s}, \qquad (1)$$

where $M_{\rm s}$ is the magnification of the lens, θ is the tilt angle of capture surface, and θ' is the tilt angle of the image plane. Because $M_{\rm t}$ is smaller, the resolution in the tangential direction needs to reach the minimum resolution of the scanner, i.e. 500 ppi. This value corresponds to one pixel size in image space, which in this design is 5.2 μm, with the Nyquist frequency of 96 lp/mm. For a 45° angle prism with index of refraction 1.5163, the resolution of sagittal direction is 705 ppi, corresponding to the spatial frequency of 68 lp/mm.

The design of the lens and the resulting MTF curves are shown in Fig. 3 (the computation has been performed with ZEMAX®). The first lens close to the prism acts as a field lens, reducing the height of the off-axis rays from the capture surface. As the capture area is rectangular, the top of that lens can be cut to make the system compact. When optical system is optimized, the telecentricity in both the object and the image space is controlled to a small level avoiding the introduction of trapezoid distortion. Also, minimizing the number of optical elements is important in ensuring that the finished scanner can achieve high performance.

The designed system attains excellent optical quality and approaches diffraction limit. The astigmatism of the scanner in the entire capture area was less than 0.025 mm, and other aberrations were kept at a very small level too. As shown in Fig. 3, the MTF values of this design are above 0.6 of 96 lp/mm and above 0.72 of 68 lp/mm.

Next, rectangular distortion remains will be corrected by an electronic system. A binary quadratic equation is used to establish rectangle distortion correction function as

$$\begin{cases} x = a_{00} + a_{01}v + a_{02}v^2 + a_{10}u + a_{11}uv + a_{20}u^2 \\ y = b_{00} + b_{01}v + b_{02}v^2 + b_{10}u + b_{11}uv + b_{20}u^2 \end{cases}, \quad (2)$$

where the coordinates without distortion are u and v, the distorted (rectangular) coordinates are x and y. With a no rotation rectangle distortion image, Eq. (2) can be simplified as

$$\begin{cases} x = a_{01}v + a_{10}u \\ y = b_{01}v + b_{10}u \end{cases}, \quad (3)$$

where a_{ij} and b_{ij} can be defined by knowing the control point, and the coordinates u and v can be easily processed with an electronic system using a high speed field programmable gate array (FPGA).

A fingerprint scanner was assembled and tested according to the above design, a model of which is shown in Fig. 4. Note that the light source is not installed in the same position as in Fig. 1, but it acts upon the same principle. This installation of LED arrays supplies more uniform illumination.

The grid distortion test image is shown in Fig. 5, in which the dimension of the test grid is 36×36 (mm). Departure from theoretical position in all grid lines is within one pixel. In this instance, distortion is smaller than 1% in all testing areas. The FBI CFT IAFIS Test Chart (contains line pairs at range from 1 to 10 cy/mm) is used for the contrast transfer function (CTF) test shown in Fig. 5. The MTF curves converted from CTF test are shown in Fig. 6. From Fig. 6, the MTF values of the fingerprint scanner are better than 0.4 in the sagittal direction and better than 0.2 in the tangential direction, both of 10 lp/mm in

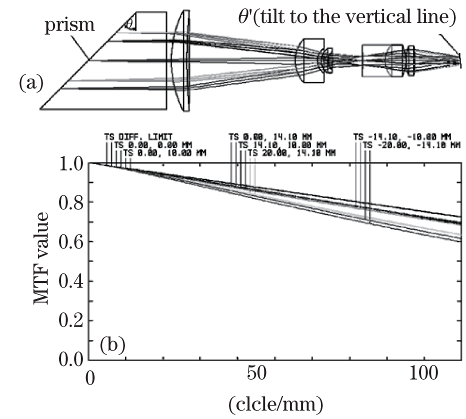

Fig. 3. Optical system of hybrid distortion correction scanner: (a) layout of optical system; (b) MTF curves of the system.

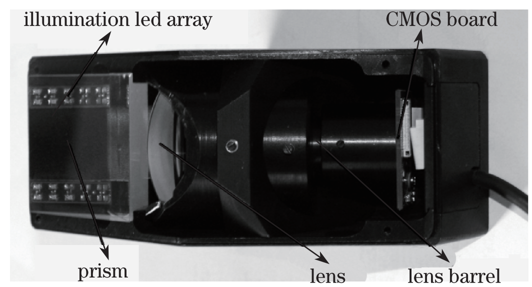

Fig. 4. Module of hybrid distortion correction fingerprint scanner.

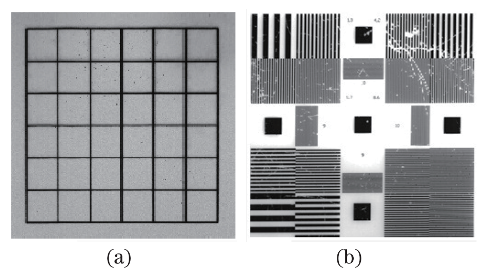

Fig. 5. Test images of fingerprint scanner: (a) test image of grid square; (b) test image of resolution target.

object space (corresponding to 97.7 lp/mm in CMOS sensor). Note that taking into account the MTF loss of the electronic system with CMOS sensor[12], the performance of the optical system after alignment is considered to be approaching theoretical level.

A real fingerprint test is shown in Fig. 7. These images are part of the whole capture area. A zoomed-in image of the square range marked in Fig. 7(b) is shown in Fig. 7(d). In comparison, a fingerprint image of the same finger as captured by a compound prism fingerprint scanner is shown in Fig. 7(a), with a zoomed portion marked in Fig. 7(a) is shown in Fig. 7(c). As we can see from these pictures, the fingerprint image captured from hybrid distortion correction fingerprint scanner is much sharper, records detailed information, and the sweat pores on the skin are distinguishable.

In conclusion, we present a high performance optical design (designed MTF>0.6 of 96 lp/mm in all capture

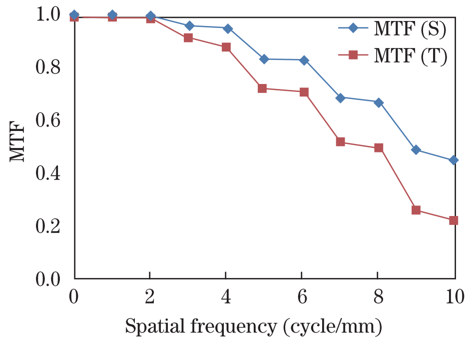

Fig. 6. MTF curves of hybrid distortion correction scanner.

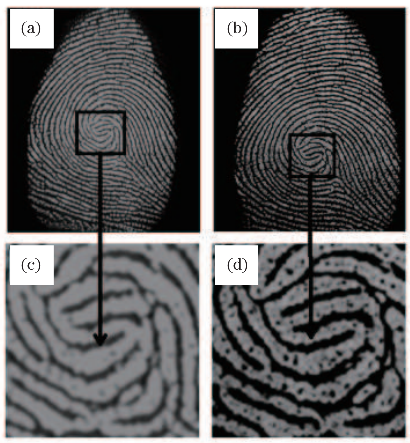

Fig. 7. Real finger test: (a) fingerprint image captured by compound prism scanner; (b) fingerprint image captured by hybrid distortion correction scanner; (c) zoomed portion from image by compound prism scanner; (d) zoomed portion image by hybrid distortion correction scanner.

area) for a rolling fingerprint scanner which simultaneously achieves large capture size (40×40 (mm)) and high object space NA (0.022). This system applies a double telecentric lens and a electronic system in correcting trapazoid distortion (the distortion as built <1%), and a dark field illumination approach in increasing the contrast and dynamic range of fingerprint images. A scanner based on the presented design was realized and tested successfully.

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