Abstract—High-resolution automated fingerprint recognition systems (AFRSs) offer higher security because they are able to make use of level-3 features, such as pores, that are not available in lower resolution (< 500-dpi) images. One of the main parameters affecting the quality of a digital fingerprint image and issues such as cost, interoperability, and performance of an AFRS is the choice of image resolution. In this paper, we identify the optimal resolution for an AFRS using the two most representative fingerprint features: minutiae and pores. We first designed a multiresolution fingerprint acquisition device to collect fingerprint images at multiple resolutions and captured fingerprints at various resolutions but at a fixed image size. We then carried out a theoretical analysis to identify the minimum required resolution for fingerprint recognition using minutiae and pores. After experiments on our collected fingerprint images and applying three requirements for the proportions of minutiae and pores that must be retained in a fingerprint image, we recommend a reference resolution of 800 dpi. Subsequent tests have further confirmed the proposed reference resolution.

Index Terms—Fingerprint recognition accuracy, high-resolution automated fingerprint recognition systems (AFRSs), minutiae, pores, selecting resolution criteria.

I. INTRODUCTION

As one of the most popular biometric traits, fingerprints are widely used in personal authentication, particularly with the availability of a variety of fingerprint acquisition devices and the advent of thousands of advanced fingerprint recognition algorithms. Such algorithms make use of distinctive fingerprint features that can usually be classified at three levels of detail [1], as shown in Fig. 1 and referred to as level 1, level 2, and level 3. Level-1 features are the macro details of fingerprints, such as singular points and global ridge patterns, e.g., deltas and cores (indicated by red triangles in Fig. 1). They are not very distinctive and are thus mainly used for fingerprint classification rather than recognition. The level-2 features (red rectangles) primarily refer to the Galton features or minutiae, namely, ridge endings and bifurcations. Level-2 features are the most distinctive and stable features, which are used in almost all automated fingerprint recognition systems (AFRSs) [1]–[3] and can reliably be extracted from low-resolution fingerprint images (~500 dpi). A resolution of 500 dpi is also the standard fingerprint resolution of the Federal Bureau of Investigation for AFRSs using minutiae [4]. Level-3 features (red circles) are often defined as the dimensional attributes of the ridges and include sweat pores, ridge contours, and ridge edge features, all of which provide quantitative data supporting more accurate and robust fingerprint recognition. Among these features, pores have most extensively been studied [4]–[17] and are considered to be reliably available only at a resolution higher than 500 dpi.

Resolution is one of the main parameters affecting the quality of a digital fingerprint image, and so, it has an important role in the design and deployment of AFRSs and impacts both their cost and recognition performance. Despite this, the field of AFRS does not currently have a well-proven reference resolution or standard resolution for high-resolution AFRS that can be used interoperably between different AFRSs. For example, Stosz and Alyea extracted pores at a resolution of approximately 1270 dpi in the vertical direction and 2400 dpi in the horizontal direction (1270 dpi \times 2400 dpi) [5]. Jain et al. chose a resolution of 1,000 dpi based on the 2005 ANSI/NIST fingerprint standard update workshop [4]. The Committee to Define an Extended Fingerprint Feature Set [12] defined level-3 features at a resolution of 1000 dpi. Zhao et al. proposed some pore extraction and matching methods at a resolution of 902 dpi \times 1200 dpi [9]–[11]. Finally, the International Biometric Group analyzed level-3 features at a resolution of 2000 dpi [13].

In this paper, we take steps toward establishing such a reference resolution, assuming a fixed image size and making use of the two most representative fingerprint features, i.e., minutiae and pores, and providing a minimum resolution for pore extraction that is based on anatomical evidence. The use...
of a fixed image size is determined by the fact that the quality of a digital fingerprint image is mainly determined by three factors, the resolution, the number of pixels in a fingerprint image, and the measured area of the fingerprint, with it being possible to uniquely determine the value of any one given the other two. In analyzing the influence of resolution on AFRS, it was thus necessary to fix one of the other two parameters. Here, we choose to fix the image size. We conducted experiments on a set of fingerprint images of different resolutions (from 500 to 2000 dpi). By evaluating these resolutions in terms of the number of minutiae and pores, the results have shown that 800 dpi would be a good choice for a reference resolution. Finally, we applied state-of-the-art automated fingerprint recognition algorithms to our collected fingerprint images. Via cross-validation experiments, we found the recognition precision under resolution 700–1000 dpi is one order of magnitude higher than that under other considered resolutions. The highest recognition accuracy in different fingerprint groups is almost always obtained under 800 dpi. These results validate our proposed resolution from the point of view of automated fingerprint recognition accuracy.

The rest of this paper is organized as follows. Section II describes how we assembled the collection of multiresolution fingerprint images publicly available. We therefore collected a multiresolution fingerprint image database by using our custom-built fingerprint image acquisition device. In this section, we introduce the fingerprint acquisition device and the established multiresolution fingerprint image database.

II. COLLECTING MULTiresOLUTION FINGERPRINT IMAGES

According to our knowledge, there is no data set of multiresolution fingerprint images publicly available. We therefore collected a multiresolution fingerprint image database by using our custom-built fingerprint image acquisition device. In this section, we introduce the fingerprint acquisition device and the established multiresolution fingerprint image database.

A. Acquisition Device

A multiresolution fingerprint acquisition device (or sensor) must be cost-effective but should particularly be able to acquire fingerprint images at multiple resolutions without any negative impact on the quality of the image [2]. There are generally three kinds of fingerprint sensors: solid state, ultrasound, and optical [2], [18]. Solid-state sensors are small and inexpensive but cannot capture high-resolution images [19]. Ultrasound sensors can capture high-resolution images but are usually bulky and expensive [20]. Optical sensors can capture a variety of different image resolutions, varying in a range of sizes and prices. They are easy to implement and have been found to have a high degree of stability and reliability [21]. Our system is thus equipped with an optical fingerprint sensor.

While there are also several different ways to implement optical fingerprint sensors, the oldest and most widely used way [2] and the way we have chosen to implement our sensor is frustrated total internal reflection (FTIR). As shown in Fig. 2, an FTIR-based fingerprint sensor consists of a light source, a glass prism, a lens, and a charge-coupled device (CCD) or complementary metal–oxide–semiconductor camera. When users put their fingers on the surface of the glass prism, ridges absorb light, and so, they appear dark, whereas valleys and the fine details on ridges reflect light and thus appear bright. Different resolutions can be obtained by simply adjusting the distance between the glass prism and the lens and the distance between the lens and the camera.

B. Fingerprint Samples

The most commonly used fingers in fingerprint recognition are the thumb, index finger, and middle finger. These are also the fingers that we use for the images used in our experiments. We collected fingerprint images from both males and females. This is pertinent because male and female fingers are, on the average, different in terms of area and ridge width (or pore size). A total of 25 males and 25 females contributed to our database. Four fingerprint images were captured from each of their six fingers (i.e., thumb, index, and middle fingers on right and left hands) under each of the following resolutions: 500, 600, 700, 800, 900, 1000, 1200, 1600, and 2000. As a result, there are totally 1200 fingerprint images for each of the considered resolutions in the database. Fig. 3 shows some example fingerprint images collected from a male and a female.

C. Implementation of Multiresolution

Three factors among others can affect the quality of a fingerprint image: its resolution, the measured area of the fingerprint that is captured or sensed, and the size of the image (the number of pixels). These factors are essentially not independent but related with each other as follows:

\[ H = 25.4 \times \frac{h}{r} \quad W = 25.4 \times \frac{w}{r} \]  

where \( r \) denotes the resolution, \( h \) and \( w \) denote the height and width of the image, and \( H \) and \( W \) denote the height and width of the captured area (in millimeters). To generate fingerprint
images of different resolutions, one of the other two parameters must be fixed. Table I shows the values of $H$ and $W$ according to (1) at different resolutions when $h$ and $w$ are set as 640 and 480 pixels. It can be seen that, at a fixed image size, the area captured by the image decreases as the resolution increases. Different resolutions can easily be obtained by adjusting the distances between the glass prism, the lens, and the CCD. Fig. 4 shows some example fingerprint images at different resolutions.

It should be noted that the resolution of our device is not identical along the vertical and horizontal directions. This is because the CCD camera has a vertical resolution of 1040 lines and a horizontal resolution of 1394 lines. At 500 dpi, this is not a large difference, and researchers usually ignore it. However, as the resolution increases, the difference between the vertical and horizontal resolutions becomes more obvious. For example, at a vertical resolution of 800 dpi, the horizontal resolution is 1064 dpi, but at a vertical resolution of 1200 dpi, the horizontal resolution is 1596 dpi. The ratio between the horizontal resolution and vertical resolution is equal to the one between the horizontal resolution and vertical resolution of the CCD camera. Thus, given both the vertical or horizontal resolution of fingerprint images and the parameters of CCD camera, we can calculate the resolution of fingerprint images along the other direction. For simplicity, in this paper, we refer just to the vertical resolution.

III. SELECTING RESOLUTION CRITERIA USING MINUTIAE AND PORES

Generally, people may think that higher recognition accuracy can be achieved by increasing the resolution. It is true if the whole fingerprint region is covered. However, in practical AFRSs, the fingerprint image size is usually confined to a relatively small one for the purpose of miniaturization and reducing the computational complexity. Until now, the most widely used image size in most papers [6]–[17] or in most public fingerprint image databases such as the fingerprint verification competition (FVC) databases (e.g., FVC2000, FVC2002, FVC2004, and FVC2006) is $640 \times 480$ pixels. With a limited image size, the larger the resolution is, the smaller the captured fingerprint region will be. Although increasing the fingerprint image resolution can provide more fine details on fingerprints for fingerprint matching, it would degrade the fingerprint recognition accuracy if the lost of useful discriminative information (e.g., minutiae) due to decreased fingerprint areas dominates the newly emerged fingerprint details (e.g., pores). For instance, the fingerprint images of a fixed size might cover the whole fingerprint regions at low resolution but capture only few ridges on the fingers at high resolution (see Fig. 4). Thus, in this paper aiming at a balance between various fingerprint features (in particular, minutiae and pores) available on high-resolution fingerprint images, we investigate the fingerprint distinctiveness and recognition accuracy at different resolutions when a fixed image size is adopted. It is also worth mentioning that noise caused by the skin condition or the amount of pressure applied by the finger [2] also plays an important role in the recognition performance of AFRS due to its influence on the quality of fingerprint images. However, it is a common issue to fingerprint images at all resolutions and is thus out of the scope of the resolution selection work in this paper.
Since 500-dpi minutiae-based AFRSs were taken as the baseline systems, we chose the fingerprint image size so that as many minutiae as possible are captured by the 500-dpi fingerprint image, or in other words, it can cover the full fingerprint region. By experience, we used an initial image size of 640 x 480 pixels. As can be seen in Fig. 4, this size can actually capture the full fingerprint region at resolutions of 500 and 600 dpi as well. Thus, we cropped the foreground fingerprint regions on these 500-dpi fingerprint images by using rectangles. The maximum width and height of these rectangles observed in the database are 380 and 360 pixels, which were finally taken as the image size for the fingerprint images captured under higher resolutions (i.e., 600–2000 dpi in the experiments in this paper). Such an image size, which may be comparable with the templates stored in most of existing minutiae-based AFRSs, will be very helpful to realize the interoperability between different AFRSs, which is one motivation of this paper.

To utilize the minutiae and pores on fingerprints, it is necessary that we be able to robustly extract both of these features. Minutiae can robustly be extracted from images of 500 dpi or above but pore extraction requires higher resolution images according to investigating most of the papers about fingerprints’ studies [1]–[18], [22]. It thus became necessary to figure out what would be the minimum resolution needed to extract pore features. Intuitively, such a figure can be arrived at based on anatomical evidence, i.e., the possible smallest physical size of pores on fingers. We will discuss this in detail in Section IV-A.

We finally raised three criteria to select the image resolution for high-resolution AFRSs by considering the following.

1) Given a fixed image size, retain as many minutiae as possible while pores begin to be available.
2) The number of pores begins to decrease, and no other useful information but the position of pores will be conveyed when resolution reaches a certain value.
3) Minutiae are more discriminative than pores if the same number of them is considered. Retain as many minutiae as possible while also retaining an acceptable number of pores.

We can better understand the rationale for the criteria by considering the images of an example finger shown in Fig. 5, whose image size is 380 x 360 pixels and resolution increases from 500 to 2000 dpi. The minutiae are the features of interest and are marked with red circles. The availability of pores can also be seen on these images. One may clearly observe the change of available minutiae and pores across these fingerprint images of different resolutions. Next, we introduce the three selection criteria in detail.

Criterion 1: Given a Fixed Image Size, Retain as Many Minutiae as Possible While Pores Begin to Be Available. A Lower Limit Image Resolution Can Be Obtained: As can be seen in Fig. 5, the size and shape of pores become more visible at higher resolutions. However, according to [1] and [6], usually, only the location of pores is reliable discriminative information for fingerprint recognition; on the contrary, the size and shape of one pore can significantly vary from one impression to another. The two 2000-dpi images in Fig. 6 are from the same finger but collected at different times. Clearly, the pores’ size and shape (see the pores marked by red circles) are corrupted by noise or influenced by the condition of pores (open or closed). We thus set another criterion for resolution selection based on the
Criteria 3: Minutiae Are More Discriminative than Pores If the Same Number of Each Is Considered. Retain as Many Minutiae as Possible While Also Retaining an Acceptable Number of Pores. A Reference Image Resolution Is Then Proposed: Criteria 1 and 2 put emphasis on the number of minutiae and pores, respectively, which just offer the lower resolution and upper resolution for high-resolution AFRSs. However, it is obvious that this will at times also require us to make some kind of tradeoff between the two. In this tradeoff, the bias will be toward retaining minutiae because the distribution of minutiae is more random than that of pores, and so, the number of minutiae in an image will have a greater influence on fingerprint recognition. The blue line on Fig. 7 links ten adjacent minutiae on a fingerprint image, while the red line links adjacent pores. We can see that the blue line traverses approximately 1/3 of the entire fingerprint image while the red line is concentrated in just one area of about 1/100 of the fingerprint image. From this, it would seem that if one or the other, i.e., minutiae or pores, must be traded off, then we lose less discriminative power if we bias toward retaining minutiae in the selection of a suitable resolution. We thus set our last criterion for resolution selection as retaining as many minutiae as possible while an acceptable number of pores are available.

Note that all the aforementioned three criteria are about the number of minutiae and pores with a fixed image size. However, the ridge width, which differs between different kinds of fingers (e.g., thumb, index finger, and middle finger) [23] and between different genders (female and male) [24], also has some effect on the number of minutiae and pores for a fixed image size and would consequently affect the selection of resolution. To make the reference resolution we selected based on the established criteria being universal to all fingers, it is necessary to study the relationship between the ridge width and the resolution. An analysis of ridge width on different kinds of fingers (e.g., thumb, index finger, and middle finger) and on fingers from different genders (female and male) is conducted with respect to the resolution selected based on the established criteria. Section IV-C will report the analysis result.

IV. EXPERIMENTS AND ANALYSIS

To get a reference resolution based on our established criteria and to verify it, some analysis and experiments are organized as follows. First, a theoretical analysis of the minimum resolution for pore extraction is given. Second, the statistical number of minutiae and pores manually counted is offered. Third, an analysis of the ridge width on different kinds of fingers (thumb, index finger, and middle finger) and on fingers of different genders (female and male) is given. Finally, the automated fingerprint recognition results of different resolution fingerprint images are provided.

A. Selecting the Minimum Resolution Required for Pore Extraction

There is a minimum resolution that is required to be able to extract pores well. In 1994, Stosz and Alyea [5] automatically extracted pores using a high-resolution fingerprint sensor. They noted that pores could range in size from 60 to 250 μm in one dimension and that the smallest detectable pores, i.e., 60 μm in one dimension, determined the minimum resolution required by a sensor. They assumed a sampling period half the size of the smallest pore and concluded that the minimum required a resolution of 800 dpi. In a later paper, in 1997, Roddy and Stosz [6] talked about a range of pore sizes of 88–220 μm. Taking these two figures into account, in this paper, we use the average of these two minimum pore sizes.

To determine the minimum required resolution, we take the size of pores and the resolution and apply (1) to calculate the number of pixels in a pore. Then, based on the rule that the size of the smallest pores in one dimension can be downsampled [5], we know that the minimum resolution for pore extraction should guarantee that there are at least 2 pixels of the smallest pores in one dimension, as illustrated in Fig. 8. Table III shows the minimum values of height $h$ for different resolutions. We can see that the minimum resolution required for pore detection

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Fig. 7. Distribution of a similar number of minutiae and pores on a fingerprint image of $380 \times 360$ pixels.

Fig. 8. Rule used to choose the minimum resolution for pore extraction.
is 700 dpi when assuming a sampling period half the size of the smallest pores.

B. Selecting the Resolution Based on the Established Criteria

Given a fixed image size, as resolution increases, the number of minutiae decreases and pores become more visible. We manually counted the numbers of minutiae and pores in the 120 fingerprint images at each resolution (500 dpi × 2000 dpi) at an image size of 380 × 360 pixels and then averaged these numbers. Fig. 9 shows the relationship between the numbers of minutiae and pores. We have exaggerated the number of minutiae tenfold for the purpose of display. We can see that the number of minutiae is monotonically decreasing but within an acceptable range from 500 to 1000 dpi and that a relatively large number of pores (statistical number by counting manually) are retained at resolutions in the range of 700–1000 dpi. It would appear that the best choice of resolution for fingerprint recognition is 700 dpi. However, given that 700 dpi is the minimum resolution for pore extraction, we decided that to make the system more robust to noise, 800 dpi would be a better choice.

C. Analysis of Ridge Width

Since minutiae and pores are both related to fingerprint ridges, there is some influence of ridge width on the number of minutiae and pores. We thus did some analysis about the ridge width for different groups of fingers. Ridge width has been studied in [23] and [24]. In [23], the ridge width was determined by counting the ridges transversely crossing a line of 1 cm. In the paper, the authors concluded that ridge width has little to do with the body weight, stature, hand length, and so on. They also summarized that the ridge width is different for different fingers even though they do not greatly differ. However, they did not discuss the relationship between ridge width and gender, for the reason that all the samples used in their paper are from males. The relationship between ridge width and gender was studied in [24]. Ridge width in that paper was decided by the ridge density, which counted the epidermal ridges on fingerprints with a 5 mm × 5 mm square drawn on transparent film. The authors of [24] concluded that women tend to have a statistically significant greater ridge density. Getting aware of the variation of ridge width, we also studied the ridge width on different kinds of fingers (e.g., thumb, index finger and middle finger) and on fingers from different genders (female and male) by using our collected fingerprint image database at the selected resolution 800 dpi. The ridge density used in [24] is adopted here to determine the ridge width. In our database, there are 150 female fingers, 150 male fingers, 100 thumbs, 100 index fingers, and 100 middle fingers. Some descriptive statistics of dermal ridge densities as mentioned in [24] and the corresponding ridge width represented in terms of micrometers [calculated by the following (2)] and pixels [calculated by formula (1)] are given for different groups of fingers in Table IV. The corresponding ridge width represented in terms of micrometers is calculated as follows:

\[
\text{ridge width} = \sqrt{(5^2 + 5^2)}/(\text{ridge density} \times 2). \tag{2}
\]

Here, the diagonal length of the 5 mm × 5 mm square is considered as the overall length of all ridge–valley period.

Table IV shows the standard variation (SD), mean value (Mean), minimum value per person (Minimum), and maximum value per person (Maximum) of the ridge density, as well as their corresponding ridge width on different groups of fingers. The results of different kinds of fingers (thumb, index finger, and middle finger) in Table IV show that there is little difference in ridge width between them, which agrees with the conclusion made in [23]. The results in Table IV also show that the ridge width of females is generally smaller than that of males by 15 μm or 0.5 pixels. However, this difference is not significant (i.e., of subpixel level). Thus, we conclude that, under a resolution of 800 dpi, the ridge width had little influence on the number of minutiae and pores. It makes our proposed reference resolution universal to all fingers.

D. Fingerprint Recognition Accuracy

To verify our choice of resolution and its relationship to accurate fingerprint recognition, we conducted a series of experiments using the fusion strategy presented in [10] by combining the state-of-the-art minutia-based method proposed in [22] and the pore-based method proposed in [10], evaluating recognition accuracy according to the equal error rate (EER). Specifically, we did cross-validation experiments by dividing all fingers into three groups according to the types of fingers (i.e., thumb, index

![Table III: The Minimum Value of h of Different Resolutions](image-url)
TABLE IV  
DESCRIPTIVE STATISTICS COMPARISONS OF RIDGE DENSITY AND THEIR CORRESPONDING RIDGE WIDTH ON DIFFERENT GROUP OF FINGERS

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th>Males</th>
<th>Thumb</th>
<th>Index Finger</th>
<th>Middle Finger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fingers</td>
<td>150</td>
<td>150</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Mean (ridges/25 mm²)</td>
<td>19.13</td>
<td>17.67</td>
<td>18</td>
<td>18.23</td>
<td>18.67</td>
</tr>
<tr>
<td>Corresponding ridge width (unit: pixel)</td>
<td>(185, 5.8)</td>
<td>(200, 6.3)</td>
<td>(196, 6.2)</td>
<td>(194, 6.1)</td>
<td>(189, 6.0)</td>
</tr>
<tr>
<td>Minimum* (ridges/25 mm²)</td>
<td>16.83</td>
<td>15.50</td>
<td>16.13</td>
<td>16.00</td>
<td>16.67</td>
</tr>
<tr>
<td>Corresponding ridge width (unit: pixel)</td>
<td>(210, 6.6)</td>
<td>(228, 7.2)</td>
<td>(219, 6.9)</td>
<td>(220, 6.9)</td>
<td>(212, 6.7)</td>
</tr>
<tr>
<td>Maximum* (ridges/25 mm²)</td>
<td>22.67</td>
<td>21.67</td>
<td>21.17</td>
<td>21.77</td>
<td>22</td>
</tr>
<tr>
<td>Corresponding ridge width (unit: pixel)</td>
<td>(156, 4.9)</td>
<td>(163, 5.1)</td>
<td>(167, 5.3)</td>
<td>(162, 5.1)</td>
<td>(161, 5.1)</td>
</tr>
<tr>
<td>SD (Standard Variation)</td>
<td>1.85</td>
<td>1.26</td>
<td>1.89</td>
<td>2.08</td>
<td>2.16</td>
</tr>
</tbody>
</table>

*Based on the average number of ridges/25 mm² per person [24].

Fig. 10 shows the EERs on different groups of fingers at different resolutions by fusing the state-of-the-art minutia-based method proposed in [22] and the pore-based method proposed in [10]. Specifically, the black line in Fig. 10 shows the recognition results when only the males’ fingers in our database are considered. The lowest EER is obtained when resolution is 700 dpi. The red line in Fig. 10 shows the EER values at different resolutions when only females’ fingers in our database are involved. The lowest EER is obtained when the resolution is 900 dpi. The gray line that represents the EERs when all fingers in our database are considered shows that the lowest EER can be obtained when the resolution is 900 dpi. The green line at the bottom that represents the EERs at different resolutions when all fingers in our database are considered shows that the lowest EER can be obtained when the resolution is 800 dpi. However, all of the results in Fig. 10 show that a relatively lower EER can be obtained when the resolution is between 700 and 1000 dpi. A resolution of 800 dpi.
can achieve the lowest EER in most cases and the lowest mean EER of the sixfold experiment (pink line). This result further confirms our proposed reference resolution.

V. Conclusion

This paper has proposed a method for selecting a reference resolution for use in high-resolution AFRSs based on minutiae and pores. We have initially found that, based on anatomical evidence, a minimum resolution of 700 dpi would give good results, but further analysis based upon an analysis of the number of minutiae and pores and the ridge width on different kinds of fingers and on fingers of different genders, as well as tests of comparative accuracy, has led us to recommend a reference resolution of 800 dpi. While we have regarded this as an advance, we must point out that the image size also has an important role in high-resolution AFRSs. In this paper, we limited images to a size of 380 × 360 pixels to allow us to investigate only the impact of resolution. In future work, we will investigate how to best make the tradeoff between the influences of resolution and image size within a certain range on high-resolution AFRS and to figure out whether there exists a dynamic resolution to different image sizes for high-resolution AFRSs.

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