

This document is downloaded from DR-NTU, Nanyang Technological University Library, Singapore.

Title	Iris recognition using stable dark features
Author(s)	Liu, Bo; Lam, Siew-Kei; Srikanthan, Thambipillai; Yuan, Weiqi
Citation	Liu, B., Lam, S.-K., Srikanthan, T., & Yuan, W. (2013). Iris recognition using stable dark features. <i>Journal of computers</i> , 8(1), 41-48.
Date	2013
URL	http://hdl.handle.net/10220/23982
Rights	© 2013 Academy Publisher. This paper was published in <i>Journal of Computers</i> and is made available as an electronic reprint (preprint) with permission of Academy Publisher. The paper can be found at the following official DOI: [http://dx.doi.org/10.4304/jcp.8.1.41-48]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Iris Recognition Using Stable Dark Features

Bo Liu

Computer Vision Group, Shenyang University of Technology,
Shenyang, China
Email: liuboapp@hotmail.com

Siew-Kei Lam, Thambipillai Srikanthan
Centre for High Performance Embedded Systems,
Nanyang Technological University, Singapore
Email: {assklam, astsrikan}@ntu.edu.sg

Weiqi Yuan

Computer Vision Group, Shenyang University of Technology,
Shenyang, China
Email: yuan60@126.com

Abstract—We propose a novel approach for iris recognition in less constrained environments that takes into account imaging noise arising from image capture outside the Depth of Field (DOF) of cameras. The proposed approach utilizes stable dark regions in iris images for recognition and does not rely on special hardware or on computationally expensive image restoration algorithms. We have employed a Gabor-based model to establish that stable features, which are not sensitive to defocus, correspond to local regions in iris images with low gray-level intensity. We will also present an approach to identify stable bits from the iris code representation, which correspond to dark regions in the enrolled image. Only these stable bits are used for recognition. Experimental results based on 15,000 images with varying degree of defocus show that the proposed method achieves an average recognition performance gain of about 1.45 times over a conventional method that relies on the entire code representation for iris recognition.

Index Terms—iris recognition, dark features, defocused iris images

I. INTRODUCTION

Conventional iris recognition methods often require a high quality image input, which typically entails considerable inconvenience to users as they are subjected to various constraints during image acquisition. For example, the subject must position themselves such that their eye is within the limited DOF of the camera system. This is required as iris images captured outside the DOF of cameras are transformed by blurring caused by optical defocusing [1], which results in low recognition performance. This problem has become more severe with the growing number of secure applications in mobile handheld devices that require a good identification

system in place for recognizing individuals. As these portable devices do not have provisions for constrained image capture, there is a need to devise iris recognition techniques that are able to operate in less constrained environments and robust enough to tolerate a certain degree of image defocus. In addition, as portable devices have strict requirements on performance and power efficiency, the iris recognition method must have low computation complexity.

In this paper, we present a novel and efficient method for recognizing defocused iris images captured outside the DOF of cameras. Our investigation reveals that iris features that are not sensitive to optical defocusing can be identified as local dark regions with low gray level intensity from an enrolled image. Experimental results confirm that good recognition performance can be achieved by limiting the feature extraction and pattern matching to these dark regions and its corresponding bits instead of using the entire iris code representation. The proposed method is well suited to be incorporated as part of a multi-biometric system (through integration with other biometric modality, e.g. facial [2] and hand recognition [3]) for light-weight and power sensitive mobile handheld systems as it does not rely on special hardware or compute intensive algorithms.

A preliminary version of the proposed method has been published in [4]. In our previous work, we have extracted stable dark features of an enrolled iris image by simply finding the average gray level intensity of the feature extraction blocks. In this paper, we present further investigations to show that the stable dark features can be more accurately obtained based on a new metric called the "degree of darkness" in the feature extraction blocks. Based on this new finding, we have developed a new approach for identifying stable dark features, which has resulted in better recognition accuracy than the method in [4]. In addition, in this paper, we have presented two new experiments to evaluate the recognition performance of

Manuscript received February 21, 2012; accepted April 19, 2012.
Corresponding author: Bo Liu (email: liuboapp@hotmail.com)

the proposed method when the stable bit extraction rate and distance range of image capture is varied. The new results further justify the effectiveness of proposed method for extending the DOF of iris recognition system.

The paper is organized as follows. In the following section, we discuss related work to highlight the limitations of existing approaches. Section III describes the proposed iris recognition system that relies on stable dark iris features. In Section IV, we present a method for identifying stable dark features from a single enrolled image based on our analysis of the iris feature characteristics in varying degree of image defocus. Next, experimental results are shown to demonstrate the benefits of the proposed method. Section V concludes the paper.

II. RELATED WORK

Previous work on extending the DOF of iris recognition system can be categorized into two main approaches: 1) using special hardware such as aspheric optics and 2) applying image restoration on the defocused images prior to recognition. The former approach employs specially designed aspheric optics to increase the focus invariance along the axis of the lens, while the latter uses mathematical models that are constructed based on certain image capture conditions to restore the defocused images. These two approaches have a common aim to enhance the quality of the captured images in order to improve the recognition performance for robust iris recognition systems.

In the first approach, computational imaging systems that commonly employ wave-front coded techniques are used [5][6]. These systems introduce a cubic phase mask in the standard optical system to produce large focus invariance and employ signal processing algorithms on the captured images. Various wave-front coded lenses have been proposed for iris recognition, which take into account the non-linear steps required for iris feature extraction and identification [7][8][9]. The work in [10][11] examined the utilization of wave-front coded imaging system for increasing the operational range of iris recognition by considering the absence and presence of post-processing methods to restore the optical defocus in images that are introduced by the aspheric optic. They have demonstrated that the use of such optical elements is capable of relaxing the DOF requirements without the need to restore the defocused images. The work in [12][13] proposed a pattern matching strategy for iris recognition of defocused images based on correlation filtering. However, this method can only be used for images captured with wave-front coded systems. The methods discussed above require special optical element insertion, large computations and in some cases generate images with lower Signal-to-Noise Ratio (SNR) [10], which must undergo post-processing prior to recognition.

The second approach aims to construct a mathematic model for restoring the defocused images prior to iris recognition. A real-time iris image restoration method

based on inverse filtering was introduced in [14][15]. However, this method did not consider noise factors. In addition, the point spread function (PSF) was heuristically determined without taking into consideration the camera optics, and this resulted in recognition performance degradation. A non-blind de-convolution algorithm to restore iris images and extend the DOF was proposed in [1]. The authors estimated the PSF using the focus score that was measured from the high frequency components of the iris regions after irrelevant objects such as eyelashes and eyelids were removed. However, the Gaussian smoothness term used in the algorithm tend to over-smooth the restored image. An iris restoration algorithm using more accurate information pertaining to the image capture conditions that are computed from the iris images was proposed in [16], which achieves better performance on both synthetic and real data set when compared with the state-of-art iris restoration algorithm. While some of the image restoration methods have shown promising results, the biggest challenge in these approaches lie in obtaining suitable information pertaining to the image capture conditions that is required to construct the mathematic model for restoring the defocused images [16]. In addition, similar to the first approach, techniques relying on image restoration algorithms have high computational complexity and do not lend themselves well towards the power sensitive requirements of mobile handheld devices.

A. Main Contribution

We proposed a method that is capable of recognizing defocused iris images captured outside the DOF of cameras without the need for special hardware or time consuming image restoration algorithms. Our investigation reveals that dark iris features are not sensitive to optical defocusing and they can be represented as stable bits in the iris code representation. Experimental results show that high recognition accuracy can be achieved by exploiting these stable bits for recognition. While previous work in [17]-[21] have reported on the prospects of using stable iris features for recognition, to the best of our knowledge, our work is the first to establish the relationship between dark features in iris images and its insensitivity to noise introduced when the images are captured outside DOF of cameras.

III. PROPOSED IRIS RECOGNITION SYSTEM

The proposed iris recognition system in less constrained environment is shown in Fig. 1. During enrollment, image acquisition obtains a high quality iris image that is captured in sharp focus within the camera DOF. For authentication, only a single iris image is needed, which may be captured at different distances from the camera's DOF.

Each image undergoes a pre-processing step consisting of localization and normalization to eliminate any non-related information (e.g. sclera, pupil, etc.) and to obtain an iris area with uniform size and shape. We have adopted the pre-processing method presented in [22] to obtain a normalized image with a resolution of 512×64 .

In order to ensure that the image used for recognition contains minimal irrelevant information, we can extract a smaller region of the normalized image for feature extraction. Based on the work in [23], we chose the mid-top area, i.e. about 40% of the whole normalized image as it has been shown to exclude features caused by irrelevant objects most of the time. The resolution of the reduced normalized image is 260×32 pixels.

In the proposed method, the stable features correspond to dark regions, which are identified from the image after pre-processing. Feature extraction is then performed on these dark regions to identify the stable bits. For feature extraction, we have applied the 2D Gabor filter [24] on the stable dark features' location in normalized iris texture images, extracted the complex phase information, and mapped them to binary codes based on their location on the complex plane as shown in Fig. 2. For example, if the phase vector (consisting of real and imaginary parts) lie in the top-right quadrant of the complex plane, it will be mapped to "11". As a result, a feature code matrix is generated for each iris image. The real part and imaginary part, each a matrix, is stored separately to facilitate our analysis on the changes in the individual bit characteristics due to the imaging noise.

The main focus of our work lies in the step to identify stable dark regions, which will be described in detail in the following section. As can be observed in Fig. 1, the stable bits in the iris code representation, which correspond to the stable features, will be stored in the database. During authentication, only the stable bits of a single individual's iris image will be matched against the stable bits in the database.

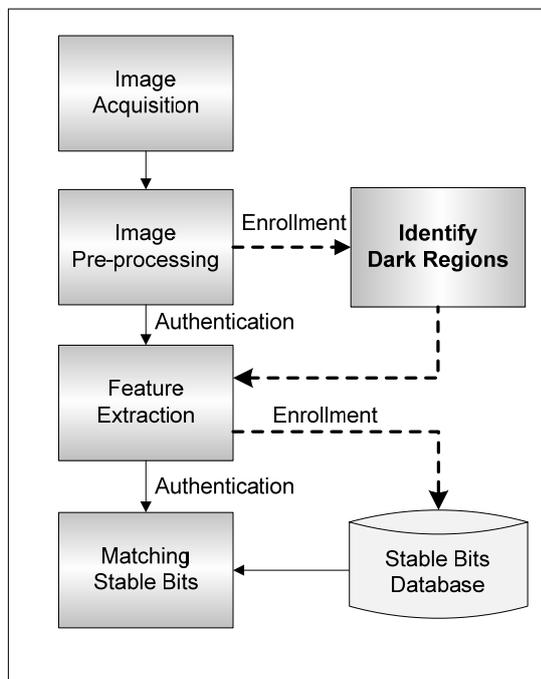


Figure 1. Proposed iris recognition that relies on stable dark features

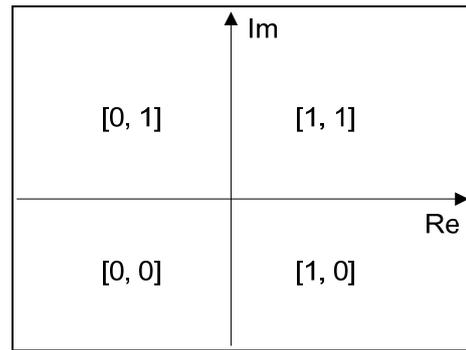


Figure 2. Phase coding

IV. IDENTIFYING DARK REGIONS FOR IRIS RECOGNITION

A. Experimental Setup

For the purpose of this study, we have employed an iris image sampling system that is controlled by a stepping motor. This enabled us to obtain 31 iris images with a fixed sampling interval of 2mm for a single eye. Fig. 3 shows an example of an iris image sequence, where the 16th image is in sharp focus as it is captured within the camera DOF. The 30 images captured before and after the clear image are subjected to varying degree of defocusing. The resolution of each image is 640×480 pixels.

The first half of the images shows the gradual decrease in defocus from the 1st image to the 16th image, while the second half of the images shows the gradual increase in defocus of the remaining images. As the sampling process of a sequence is performed with a fixed interval (i.e. 2mm apart), we can represent the degree of defocus using the image number in the sequence.

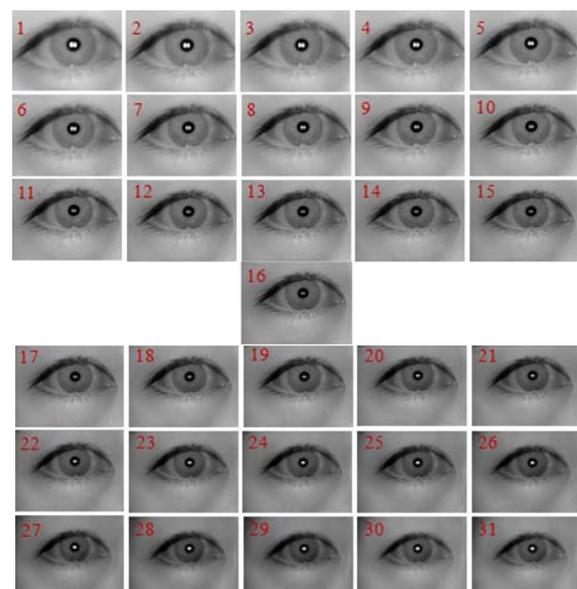


Figure 3. A sequence of iris images

For this study, we have selected 50 people, where each of their left and right eyes are sampled 5 times using the iris image sampling system. Each sampling sequence of the same eye may differ due to lighting conditions, position of the iris during image capture, etc. Incorporating such variations during image acquisition of a single eye enable us to obtain a dataset that can provide more realistic evaluations. Hence, our dataset consists of 100 classes, where each class has 5 sampling sequences and there are 31 images in each sequence. The total number of images in the dataset is 15,500 ($100 \times 5 \times 31$).

B. Stable Bits in Iris Feature Code

In this study, we aim to determine iris features that are robust to imaging noise. These features are prevalent in all the iris images of a particular sequence. As discussed above, each iris image can be converted into two feature code matrices consisting of bit patterns. Features that are invariant to imaging noise can therefore be identified by a constant bit value in the same position of the feature code matrices of the entire image sequence. Hence, our goal is to identify feature clusters from iris image sequences of an individual and perform classification of sequences from different individuals. We first make the following definitions.

Definition 1. Sensitivity: Each bit position in a feature code matrix can be defined as an intrinsic feature if the value (1 or 0) is found to be dominant across the entire sequence of images. It is defined as a sensitive feature otherwise. Sensitivity is defined as the probability of a particular bit position in the feature code matrix being a sensitive feature (in terms of %) in a sequence.

Definition 2. Stable Bit and Sensitive Bit: A bit position in the feature code matrix is defined as a stable bit when its sensitivity is less than a predefined sensitive threshold. On the other hand, if the sensitivity is higher than the predefined sensitive threshold, we denote the corresponding bit position as a sensitive bit.

Based on Definition 1 and 2, Equation (1) is used to determine whether the bit position of the feature code matrix at coordinate (x, y) is a stable bit. $F_k(i, j)$ is the feature code matrix of the k^{th} image in the sequence, n is the number of images in the sequence, and t is the predefined sensitive threshold.

$$\begin{cases} (x, y) \in \{(i, j) \mid G(i, j) \leq T_a \text{ or } G(i, j) \geq T_b\} \\ G(i, j) = \sum_{k=1}^n F_k(i, j) \\ T_a = \lfloor n \times t \rfloor \\ T_b = n - \lfloor n \times t \rfloor + 1 \end{cases} \quad (1)$$

Based on (1), Fig. 4 shows the iris feature code consisting of stable and sensitive bits for images in two classes (i.e. 1-1 and 1-2 are images from different sequences in the same class, and 9-1 and 9-2 are images from different sequences of another class). The sensitive threshold is set at 30%. The black regions correspond to the stable bits while white regions correspond to the sensitive bits. We can observe from Fig. 4 that the distribution of stable bits from different sequences in the

same class is similar with each other. In addition, the distribution of stable bits from different classes varies significantly. These observations demonstrate the feasibility of using stable bits for pattern matching to discriminate defocus iris images of different individuals.

C. Feasibility Study of Utilizing Regions with Low Intensity as Stable Features

In this section, we describe our investigation which reveals that the stable bits in enrolled images correspond to regions with local low gray level intensity, while the sensitive bits corresponds to regions with higher local gray level intensity.

Definition 3. Degree of darkness: The degree of darkness for a feature extraction block (obtained when a 17×17 Gabor filter is applied to the normalized iris image) is computed by first applying a 5×5 sub-block template to each pixel in the feature extraction block and finding the sum of all the gray levels in the sub-block template. Let's denote the sum of all the gray levels in the sub-block template as the weight of the sub-block template. The degree of darkness of a particular feature extraction block is computed as the sum of weights of 25% of all the sub-block templates with the lowest weight.

For each sharp focus image in an iris image sequence, the feature extraction blocks that correspond to the stable and sensitive bits (determined using (1)) are first identified. The average degree of darkness of the stable blocks and sensitive blocks are then computed separately. Based on this, the average degree of darkness of the stable blocks and sensitive blocks with respect to each iris class is obtained (each iris class has 5 image sampling sequences) and plotted in Fig. 5. In particular, Fig. 5 shows the average dark gray level intensity distribution of stable feature regions and sensitive feature regions of 30 different normalized iris classes. It can be observed that the stable features are mainly associated with lower average dark gray level intensity compared to the sensitive features in normalized iris images. The reason for the small difference between the two curves is due to the sub-block template size and shape that we have used in this analysis, which has resulted in the loss of certain dark features and the addition of certain irrelevant features. However, this analysis sufficiently demonstrates that in most cases, the stable bits in the iris code representation correspond to dark features in the iris images.



Figure 4. Iris feature codes from two classes (1 and 9)

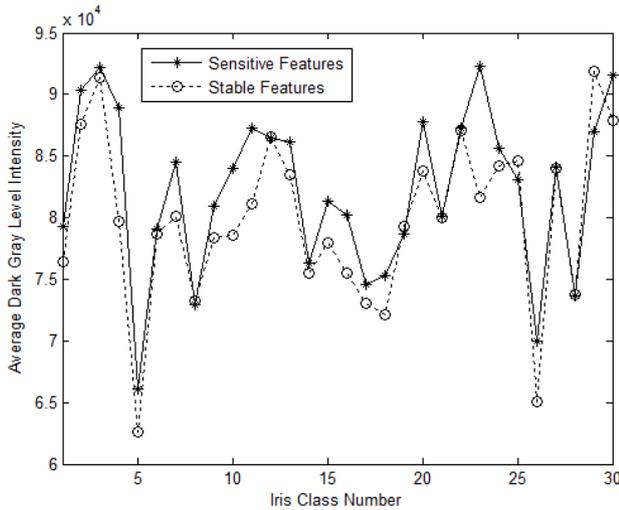


Figure 5. Average dark gray level distribution of stable and sensitive iris features from 30 different classes

Furthermore, we have applied the Gabor filter model to a synthetic image with 256 different gray level blocks that changes gradually as shown in Fig. 6. The gradual change in intensity of the generated image bears similar characteristics with the image defocus variations when the iris image is captured with increasing/decreasing distance from the camera. The corresponding encoding results (imaginary part of iris code representation) can be seen in Fig. 7. It can be observed in Fig. 7 that the encoding results for the lighter regions vary more significantly when compared to the encoding results in the darker regions. This experiment further reinforces our finding that dark features are more stable to optical defocusing of images.

D. Extracting Stable Features from Enrolled Image

Based on our finding, we devised the following method for identifying stable bits from an enrolled image. We first apply a sub-block template of window size 5x5 on each pixel in every feature extraction block of the normalized enrolled iris image to compute the degree of darkness. The degree of darkness of all the feature extraction blocks is then sorted. Based on a predefined stable bit extraction rate, we select the blocks with lowest degree of darkness as stable features. The centers of each of the selected blocks are then subjected to feature extraction using the Gabor filter to generate the stable bits for recognition.



Figure 6. Synthetic image with 256 different gray level blocks

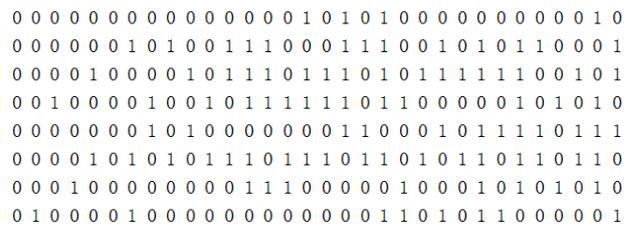


Figure 7. Encoding responding to 256 different gray level blocks

V. EXPERIMENTAL RESULTS

In this section, we present experimental results based on 15,500 images to demonstrate the feasibility of the proposed approach for iris recognition which relies on the stable dark features that are identified using the method discussed in the previous section.

We have implemented a conventional approach for iris recognition of defocused image that relies on the entire code representation (as opposed to using only stable bits in the proposed method) for purpose of comparison. In the proposed method, we have used a stable bit extraction rate of 70% to obtain the stable features from the sharp focus image for each class (the 16st image in the first sequence of each class). The experiments for the proposed method are based on images in the dataset that have not been used for identifying the stable bits.

We first evaluate the recognition performance of the proposed method that is based on identifying the stable bits from the dark regions of the iris image. Next, we evaluate the effects of changing the stable bit extraction rate on the recognition performance. Finally, we will evaluate the recognition performance of the proposed method when the images that are subjected to recognition are captured within certain predefined range from the camera.

A. Recognition Performance

Fig. 8 shows the inter-class and intra-class Hamming distance of the images in the dataset. Note that for the conventional method, the entire feature code matrix is used to calculate the Hamming distance, while only the stable bits are used in the proposed methods for calculating the Hamming distance. It can be observed from Fig. 8 that the intersection between the intra-class and inter-class distance distributions of the proposed method is smaller than the conventional method. It can be seen in Table I, that although the average inter-class and intra-class distance has been reduced in the proposed method, the intra-class distance reduction is significantly larger (i.e. 0.0346 compared to 0.0023). This results in a sharp increase in the average difference between inter-class and intra-class distances in the proposed method (i.e. 0.0915 for the conventional method, compared to 0.1238 for the proposed method).

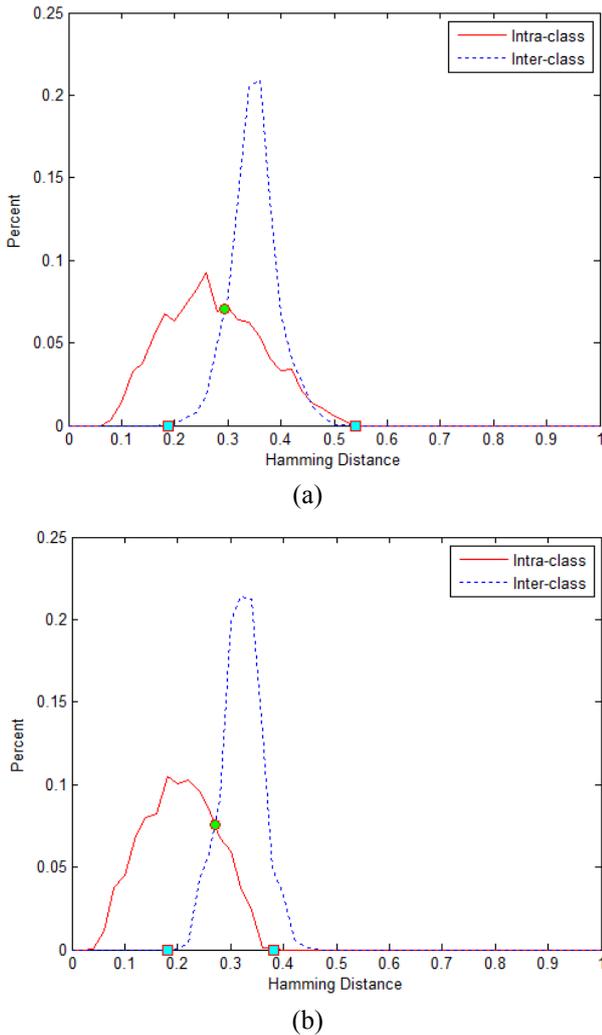


Figure 8. Distribution of inter and intra-class Hamming distances for a) conventional and b) proposed method

As shown in Table I, this leads to higher recognition performance in the proposed method. In particular, when the False Acceptance Rate (FAR) is 0.5% for both methods, the False Rejection Rate (FRR) of the conventional and proposed method is 65.86% and 47.92% respectively. Based on the Equal Error Rate (ERR), proposed method has a recognition performance gain of about 1.45 times over the conventional method respectively. These results demonstrate that the proposed methods, which rely on stable bits that are tolerant to the optical defocusing for iris recognition, are capable of discriminating iris features of individuals from different classes.

B. Effects of Stable Bit Extraction Rate on Performance

The stable bit extraction rate T , which is used to determine whether a bit position in the feature code matrix is a stable bit or not, is an important parameter as it affects the recognition performance. Table II shows how the average recognition performance (in terms of EER) changes when different stable bit extraction rates are used in the proposed method. In particular, we have

used stable bit extraction rates that are set to 60%, 65%, 70%, 75% and 80% to obtain the stable bits and evaluated the iris recognition performance for all the images in the dataset.

It can be observed that the recognition performance increases when the stable bit extraction rate is increased from 60% to 70%. Thereafter, the recognition performance decreases with further increase in the stable bit extraction rate. The effects of the stable bit extraction rate on the recognition performance is expected, as choosing a very small stable bit extraction rate will restrict the number of stable bits for recognition which could lead to low inter-class variability. On the other hand, defining a very large value for the stable bit extraction rate will lead to higher number of stable bits that are sensitive to the imaging noise and this will result in large intra-class variability, which leads to lower recognition performance.

In practice, we can also determine a suitable stable bit extraction rate to obtain a good trade-off between the recognition performance and the computational complexity of the iris recognition process.

C. Effects of Sampling Range on Recognition Performance

In order to increase the recognition performance in a non-intrusive iris recognition system, the user can be guided to position him/her-self within a certain image capture distance from the camera. It is noteworthy that such a system should not impose strict requirements on the user to position him/her-self such that the image will be captured within the DOF of the camera. Instead, the system should provide a distance range for image capture such that the entire process is comfortable to the user and can be completed fast. In this section, we evaluate the effects of varying the distance range of image capture on the recognition performance. We have chosen images under different sampling range in the iris image dataset to create the test sets. The sixteen test sets are shown in Table III, where each set contains images from varying distance range of image capture.

We evaluated the recognition performance of each test set using the conventional and proposed methods. It can be observed from Fig. 9 that the EER of both methods decreases as the distance range of image capture increases. However, the EER of the proposed method is lower than the EER of the conventional method in all cases. In addition, the EER of the conventional method increases more drastically than the proposed method. These results further justify the effectiveness of using stable dark features to extend the DOF of iris recognition system.

VI. CONCLUSION

In this paper, we proposed a method to identify stable features in iris images that are tolerant to imaging noise, which is introduced when the images are captured outside the camera DOF. Our analysis reveals that the stable bits

TABLE I.

COMPARISON OF RECOGNITION PERFORMANCE BETWEEN CONVENTIONAL AND PROPOSED METHOD

Evaluation Standard	Conventional Method		Proposed Method	
	Intra-class	Inter-class	Intra-class	Inter-class
Average Hamming distance	0.2448	0.3363	0.2102	0.3340
FRR(%) (FAR=0.5%)	65.86		47.92	
EER(%)	23.55		16.28	

TABLE II.

RECOGNITION PERFORMANCE WITH VARYING STABLE BIT EXTRACTION RATE

Performance Standard	Stable Bit Extraction Rate (%)			
	60	65	70	80
EER(%)	18.24	17.03	16.28	17.62

TABLE III.

TEST SETS THAT CONTAIN IMAGES FROM VARYING DISTANCE RANGE OF IMAGE CAPTURE

Test set No.	1	2	3	4	5	6	7	8
Image No. in sequence	16	15-17	14-18	13-19	12-20	11-21	10-22	9-23
Range of image capture (mm)	0	4	8	12	16	20	24	28
Test set No.	9	10	11	12	13	14	15	16
Image No. in sequence	8-24	7-25	6-26	5-27	4-28	3-29	2-30	1-31
Range of image capture (mm)	32	36	40	44	48	52	56	60

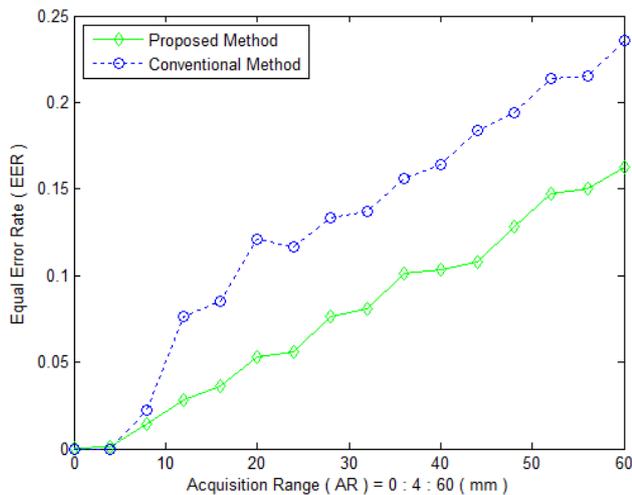


Figure 9. Relation diagram of AR and EER

corresponding to the dark features in an enrolled iris images can be identified by evaluating its average gray level value based on a predefined stable bit extraction rate. Experimental results demonstrate that superior performance recognition can be achieved by limiting the pattern matching to these stable bits instead of using the entire iris code representation. Unlike existing methods, the proposed method lends itself well towards robust, cost effective and power efficient iris recognition system for mobile handheld systems as it does not require special hardware and time consuming image restoration algorithms.

ACKNOWLEDGMENT

This work is partially supported by the National Natural Science Foundation of China under Grant No. 60672078 and the China Scholarship Council (CSC).

REFERENCES

- [1] B. J. Kang and K. R. Park, "Real-time image restoration for iris recognition systems", *IEEE Transactions on Systems, Man and Cybernetics, Part B*, Vol. 37, No. 6, December 2007, pp. 1555-1566.
- [2] Z. Peng, Y. Zhou, Y. Zhu and Z. Wen, "Application of an improved mean shift algorithm in real-time facial expression recognition", *Journal of Software*, Vol. 6, No. 1, January 2011, pp. 100-107.
- [3] H. Li and Z. Zhang, "Unstructured Fingerprint Database Matching Method Based on Grover's Quantum Algorithm", *Journal of Software*, Vol. 7, No. 10, October 2012, pp. 2301-2308.
- [4] B. Liu, S.K. Lam, T. Srikanthan, and W. Yuan, "Utilizing dark features for iris recognition in less constrained environments", *4th International Symposium on Parallel Architectures, Algorithms and Programming*, December 2011, pp. 110-114.
- [5] E.R. Dowski, Jr., and W. T. Cathey, "Extended depth of field through wave-front coding", *Applied Optics*, Vol. 34, No. 11, 1995, pp. 1859-1866.
- [6] W. T. Cathey and E. R. Dowski, "New paradigm for imaging systems", *Applied Optics*, Vol. 41, No. 29, 2002, pp. 6080-6092.
- [7] R. Narayanswamy, P. E. X. Silveira, H. Setty, V.P. Pauca, and J. Van der Gracht, "Extended depth-of-field iris recognition system for a workstation environment", *Proc. SPIE - The International Society for Optical Engineering*, March 2005, pp. 41-50.

- [8] R. Plemmons, M. Horvath, E. Leonhardt, P. Pauca, S. Prasad, et al, "Computational imaging systems for iris recognition," *Proc. SPIE - The International Society for Optical Engineering*, August 2004, pp. 346-357.
- [9] R. Narayanswamy, G. E. Johnson, P. E. X. Silveira, and H. B. Wach, "Extending the imaging volume for biometric iris recognition", *Applied Optics*, Vol. 44, No. 5, 2005, pp. 701-712.
- [10] K.N. Smith, V.P. Pauca, A. Ross, T. Torgersen, and M.C. King, "Extended evaluation of simulated wavefront coding technology in iris recognition", *Proc. Int. Conf. Biometrics: Theory, Applications, and Systems*, September 2007, pp. 316-322.
- [11] J.V.D. Gracht, V. Pauca, H. Setty, R. Narayanswamy, R. Plemmons, et al, "Iris recognition with enhanced depth-of-field image acquisition", *Proc. SPIE Visual Information Processing XIII*, Vol. 5438, 2004, pp. 120-129.
- [12] N. Boddeti and B.V.K.V. Kumar, "Extended depth-of-field iris recognition using unrestored wavefront-coded imagery", *IEEE Transactions on System, Man and Cybernetics, Part A*, Vol. 40, No. 3, May 2010, pp. 495-508.
- [13] N. Boddeti and B.V.K.V. Kumar, "Extended depth of field iris recognition with correlation filters", *Proc. 2nd IEEE Int. Conf. Biometrics: Theory, Applications and Systems*, 2008, pp. 1-8.
- [14] B.J. Kang and K.R. Park, "A study on fast iris restoration based on focus checking," *Proc. 4th Int. Conf. Articulated Motion and Deformable Objects*, July 2006, pp. 19-28.
- [15] B.J. Kang and K.R. Park, "A study on iris image restoration", *5th International Conference on Audio- and Video-Based Biometric Person Authentication*, July 2005, pp. 31-40.
- [16] X. Huang, L. Ren and R. Yang, "Image deblurring for less intrusive iris capture", *IEEE Comput. Soc. Conf. Computer Vision and Pattern Recognition Workshops*, June 2009, pp. 1558-1565.
- [17] G. Dozier, K. Frederiksen, R. Meeks, M. Savvides, K. Bryant, et al, "Minimizing the number of bits needed for iris recognition via bit inconsistency and GRIT", *IEEE Workshop on Computational Intelligence in Biometrics: Theory, Algorithms, and Applications*, Nashville, 2009, pp. 30-37.
- [18] J. E. Gentile, N. Ratha, and J. Connell, "SLIC: short-length iris codes", *Proc. 3rd Int. Conf. Biometrics: Theory, Applications and Systems*, 2009, pp. 1-5.
- [19] K. P. Hollingsworth, K. W. Bowyer, and P. J. Flynn, "The best bits in an iris code", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 31, No. 6, June 2009, 964-973.
- [20] S. Ring and K. W. Bowyer, "Detection of iris texture distortions by analyzing iris code matching results", *IEEE Proc. 2nd Int. Conf. Biometrics: Theory, Applications and Systems*, Arlington, 2008, pp. 1-6.
- [21] V. Velisavljevic, "Low-complexity iris coding and recognition based on directionlets", *IEEE Transactions on Information Forensics and Security*, Vol. 4, No. 3, September 2009, pp. 410-417.
- [22] W. Yuan and X. Bai, "A new iris edge extraction method", *Acta Optica Sinica*, Vol. 29, 2009, pp. 2158-2163.
- [23] W. Yuan, Y. Bai, and L. Ke, "Analysis of relationship between region of iris and the accuracy rate", *Acta Optica Sinica*, Vol. 28, 2008, pp. 937-942.
- [24] J. Thornton, M. Savvides, and B. V. K. V. Kumar, "An evaluation of iris pattern representation", *Proc. 1st Int. Conf. Biometrics: Theory, Applications, and Systems*, September 2007, pp. 196-201.



Bo Liu received her Bachelor's degree of Engineering in Shenyang University of Technology (SUT), Shenyang, China, in 2006. Currently, she is a PhD candidate in the school of Information Science and Engineering, SUT. She also has been a Joint PhD student in the Centre for High Performance Embedded Systems of Nanyang Technological University (NTU), Singapore from Sep. 2010 to Sep. 2011. Her research interests include biometric identification, computer vision, image processing and pattern recognition, and also intelligent embedded systems and its application.



Siew-Kei Lam received the BSc (Hons.) degree, MEng degree, and PhD in computer engineering from Nanyang Technological University (NTU), Singapore. Since 1994, he has been with NTU, where he is currently a Research Fellow with the Centre for High Performance Embedded Systems and has worked on a number of challenging projects that involved the porting of complex algorithms in VLSI. He is also familiar with rapid prototyping and application specific integrated-circuit design flow methodologies. His research interests include embedded system design algorithms and methodologies, algorithms-to-architectural translations, and high-speed arithmetic units. He is the member of the IEEE.



Thambipillai Srikanthan joined Nanyang Technological University (NTU), Singapore, in 1991. At present, he holds a full professor and joint appointments as a director of a 100 strong Centre for High Performance Embedded Systems (CHiPES). He founded CHiPES in 1998 and elevated it to a university level research centre in February 2000. He has published more than 250 technical papers. His research interests include design methodologies for complex embedded systems, architectural translations of compute intensive algorithms, computer arithmetic, and high-speed techniques for image processing and dynamic routing. He is the senior member of the IEEE.



Weiqi Yuan received his PhD degree from Northeast University (NEU), China in 1997. He is currently a professor of Shenyang University of Technology (SUT) and the dean of the school of Information Science and Engineering. He is the director of the Computer Vision Group of SUT and also the director of SUT-Texas Instruments DSP Joint Laboratory. He has published more than 200 technical papers. His main research interests include biometric identification, computer vision, image processing and pattern recognition and image capture and processing system based on DSP. He is currently a standing director of China Instrument and Control Society.