Fragile Bits in Off-angle Iris Recognition

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***Abstract*— As an emerging biometric research, standoff iris recognition systems focus on recognition of non-cooperative subjects in much less constrained environments where their captured images are likely to be non-ideal including being off-angle. Iris biometrics convert unwrapped iris textures into binary iris codes to compare them with other saved codes by measuring their Hamming Distances. The similarity calculation assumes an equal contribution of each individual pixel in iris codes. However, previous studies showed that some pixels (aka. fragile bits) are more error prone than others even in frontal iris images. In addition, off-angle iris images are affected by several challenging factors including corneal refraction and limbus occlusion. These challenges in off-angle images also increase the fragility of bits in iris codes. This paper first presents the pixel inconsistency in iris codes of off-angle images using elliptical segmentation and normalization. The pixel fragility is a result of iris codes warping due to the refraction of light in cornea and occlusion of iris texture at limbus. As another contribution, we propose to identify these fragile pixels in iris codes using edge detection and eliminating them in Hamming distance calculation by masking these fragile bits. Based on the results, the proposed method improves the recognition performance in off-angle iris images where the average genuine Hamming distance score reduced from 0.3082 to 0.1244 and the equal error rate is lowered 19%.**

Keywords—biometrics, iris recognition, fragile bits

I. INTRODUCTION

Coronavirus pandemic will likely have permanent effects on our daily life and push us for changes in how we live and move about the world. As protective measures forces us to changes our everyday routines in society to slow down the spread of the virus, it becomes more important to converting our close-contact systems to standoff and touchless including biometrics. The COVID-19 restrictions require the biometric systems to verify the individuals' identity and validate their credentials at-a-distance without requiring touching a surface or removing their mask. Among other biometric systems, iris recognition comes first as being a non-intrusive and contactless biometrics measure in addition to its accuracy, distinctiveness, and reliability [1]. However, image acquisition conditions may limit the recognition performance and hinders its possible usage in different applications. Traditional iris recognition systems capture iris images in a well-controlled environment and require taking high-quality frontal images. Therefore, non-ideal conditions including the gaze angle, occlusion, and pupil dilation lowers the performance of existing systems [2].

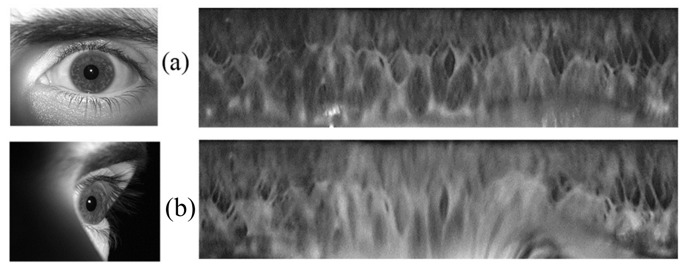

Fig. 1. Examples of (a) frontal and (b) off-angle iris images (50º in angle) with their normalized iris images.

Fig. 1 shows the examples of frontal (0º in angle) and off-angle (50º in angle) images of the same iris with their normalized images using elliptical segmentation and normalization. The effect of gaze angle difference can be easily seen between frontal and off-angle images where the texture warping distortion at normalized images is obvious. In traditional iris biometrics, the normalization step is aimed not only to convert segmented images into the same fixed size and but also to eliminate the texture deformations between images using Daugman's rubber-sheet model [1]. Since this model considers a linear deformation in the iris texture, it can address the perspective distortion. However, it does not completely compensate for the nonlinear iris deformation on images captured at different distances and angles. Therefore, the rubber-sheet model is not robust enough especially for standoff biometric systems with additional challenging degradation factors.

Standoff iris recognition requires updating the traditional algorithms to handle the non-ideal images where both cooperative and non-cooperative individuals can be recognized during their moving actions [3]. Due to the more flexible data acquisition setup in these systems compared with traditional ones, the captured iris images are more likely non-ideal images with gaze angle, pupil dilation, reflections, and occlusions. Since the accuracy of the traditional iris recognition algorithms is highly correlated with the image quality and the data capture similarity, comparison of the off- angle iris images with the frontal images degrades the recognition performance because of the corneal refraction, complex iris texture, limbus occlusion, and depth of field blur [4]. In addition, the combination of these adverse factors has more significant negative impact on the system accuracy, which requires additional efforts to eliminate their effects.

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After extracting the iris texture from the captured image using segmentation and normalization, traditional iris recognition systems convert the unwrapped grayscale iris image into a binary iris codes by applying different filters (e.g. Gabor filters) and assigning binary values based on the unit step function result of the filter quantization values. If the filter response for a specific bit is less than 0, its binary value gets 0. Otherwise, it is 1. Finally, the generated iris code is compared with previously stored codes in a database by measuring their Hamming Distances. Traditional similarity calculation methods assume an equal contribution of each individual pixel in iris codes. However, previous studies [5-10] proved the existence of fragile bits in the iris codes where some bits are more probable to flipping their binary values easier than others based on small changes in the normalized images.

This paper is organized as follows: Section 2 summarizes works related with fragile and consistent bits iris recognition. The proposed fragile bit detection and masking method for off-angle iris images are presented in Section 3. Section 4 describes the details about the off-angle iris data collection and dataset. Section 5 presents the baseline results using the traditional iris recognition algorithm, compares the results of the proposed method with a well-known fragile bit study, and discusses the important findings. Finally, we conclude in Section 6.

II. Related Works in Fragile Bits in Iris Codes

Several works related with the bit fragility, consistency, and discriminability in iris codes were presented in biometrics literature to improve the recognition performance in frontal images. The concept of bit consistency is first presented in [5] to report the robustness of some bits for the imaging noise than other fragile bits. The comparison of same iris locations in multiple images showed the fragility and consistency of bits where the consistent bits keep the same binary value, but values of fragile bits changes in significant percentage [6]. To detect the fragile bits, they used the quantization values of Gabor filters in iris encoding where the values of fragile bits are close to zero and small variations in the normalized iris may result the flip of their binary values. They sorted the quantization values of each filter, marked the bits with the smallest magnitude as fragile bits, and excluded them from the Hamming distance calculation by masking these fragile bits. For fragile bit mask generation, Dozier et al. [7] presented another approach where ten images per subject used as a training set to designate the bits as consistent if they keep their value at least 90%. In addition, they also masked the bits if they occluded more than 30%. Their method showed similar recognition performance even if 30% of the total bits are masked from the distance score calculation.

Santos and Proenca [8] proposed using the spatial and frequency distributions of consistent and fragile bits in the iris code to help with the discrimination between match and nonmatch comparisons. Instead of using HD score, they use different feature selection, dimensionality reduction, and logistic regression methods to recognize only frontal images. As an extension to fragility, Proenca [9] proposed using discriminability of bits to consider not only the bit disagreements in genuine comparisons but also the agreements of bits in impostor comparisons. This concept also suggests changing the unit step function in code quantization with sigmoid function to consider their weighted magnitude.

Instead of masking the fragile bits, Hollingsworth et. al [10] also proposed using fragile bit information in addition to the Hamming distance to recognize individuals. They suggested defining a new metric as fragile bit distance that counts the number of overlaps between the fragile bits in two different iris codes. They reported that fragile bit distance in genuine comparisons is smaller than impostor comparisons for 1372 frontal iris images. Although above mentioned studies showed a performance improvement with masking the fragile bits or using fragile bit as additional distance, they only include frontal images and ignore the off-angle images. However, fragile bits in off-angle iris images are more error prone than the frontal images because off-angle images are affected by several challenging factors including corneal refraction and limbus occlusion. Since the challenges in off-angle images also increase the fragility of bits in iris codes, fragile bits in off-angle images needs to be detected and eliminated to increase the recognition performance.

III. Methodology

Since the iris pattern is formed before birth and it is a well-protected internal organ of the eye, its pattern is accepted being stable throughout the lifespan based on the clinical evidences [11]. Therefore, the fragile bits of iris code refer to the consistency of their binary values during the quantization process not to the stability of the iris pattern. Small variations in the filter response may result flipping the binary values easily for the fragile bits. In frontal iris images, bit fragility depends on several factors including, changes in pixel coordinates due to the segmentation errors and pupil dilation, filter types in iris encoding, quantization technique for filter responses, and imaging noises and unmasked occlusions. In addition, pixel fragility in off-angle images also negatively affected by appearance warping of iris pattern due to the refraction of light in cornea and occlusion of iris texture at limbus. Therefore, this paper first presents the pixel inconsistency in iris codes of off-angle images using elliptical segmentation and normalization. Then, we propose a method to identify these fragile pixels in iris codes using edge detection and to eliminate them in Hamming distance calculation by masking the fragile bits.

Fig. 2(a-b) shows the binary iris codes of a frontal and off-angle images generated by a 2D Gabor filter in OSIRIS phase-quadrant demodulation [12] and a unit step function quantization. Although each filter generates real and imaginary responses and there are six filter outputs in total from three 2D Gabor filters, we only show a real response of the second filter due to the similar results on others. Traditional biometric systems calculate Hamming distance (HD) scores as follow:

$$\mathrm{HD} = \frac{\|(c_A \otimes c_B) \cap (m_A \cap m_B)\|}{\|m_A \cap m_B\|} \quad (1)$$

where the logical XOR ($\otimes$) compares iris codes c, and logical AND ($\cap$) excludes occlusion masks m, from the calculation. The norm ($\| \, \|$) counts the number of bits.

To show the inconsistency between frontal and off-angle images, their XOR comparison is shown in **Fig. 2**(c) where red

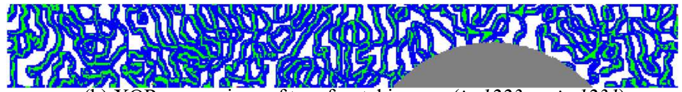
(a) Iris code of a frontal image, (*im1223*)

(b) Iris code of an off-angle image, (*im1281*)

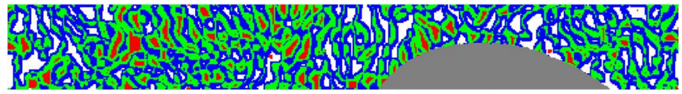
(c) XOR comparison of iris codes (*im1223 vs. im1281*)

Fig. 2. Examples of iris codes from (a) a frontal image, *im1223* (0º in angle), (b) an off-angle image, *im1281* (50º in angle), and (c) XOR comparison of frontal and off-angle iris images in (a-b). Note that, red pixels for different bits, white for same bits, and gray for the mask.

(a) Fragile bits of a frontal image, (*im1223*)



(b) XOR comparison of two frontal images (*im1223 vs. im1231*)



(c) XOR comparison of frontal and off-angle images (*im1223 vs. im1281*)

Fig. 3. Examples of iris codes from (a) a frontal image, *im1223* (0º in angle), (b) an off-angle image, *im1281* (50º in angle), and (c) XOR comparison of frontal and off-angle iris images in (a-b). Note that, red pixels for different bits, white for same bits, and gray for the mask.

pixels refer to inconsistent bits, white is for consistent, and gray shows the masks. Since the off-angle images is distorted by corneal refraction and limbus occlusion, its iris code is wrapped into different directions compared with frontal iris code. Therefore, the inconsistent regions in XOR image mainly occur at the boundary of code regions with zeros and ones. Therefore, we propose to detect the fragile bits using edge detection at iris code. Since the distortion area enlarges as the gaze angle difference between compared images increases, we also expand the fragile bit regions using dilation operation as follows:

$$f_A = \|\nabla c_A\| \oplus s_e \tag{2}$$

where fragile bits masks, f_A is computed using edge detection operation ($\|\nabla c\|$) of iris codes c, and dilation ($\oplus$) with a structing element, s_e.

Fig. 3(a) shows the fragile bits of *im1223* (in **Fig. 2**(a)) using Canny edge detection and dilation with 4x4 structuring element. Since fragile bits overlaps with the inconsistent areas in the iris code comparison and the binary values in these bits may be different based on the gaze angle differences between compared images, it is safe to exclude them from Hamming distance (HD) calculation using masking approach as follow:

$$\text{HDwFB} = \frac{\|(c_A \otimes c_B) \cap (m_A \cap m_B) \cap (f_A \cap f_B)\|}{\|m_A \cap m_B \cap f_A \cap f_B\|} \tag{3}$$

where fragile bits masks, f_A and f_B can be included to calculation as additional masks or they can be combined with their corresponding occlusion masks, m to obtain a single mask.

For better visualization of the proposed fragile bit elimination concept, **Fig. 3**(b-c) show the XOR comparison of frontal image, *im1223* with a frontal image, *im1231* (0º in angle) and an off-angle image, *im1281* (50º in angle) from the same subject, respectively. White areas are the consistent bits, green areas are the masked fragile bits, and red areas refers to inconsistent bits that cannot filtered by fragile bit mask. In the frontal image comparison as shown in **Fig. 3**(b), the proposed method masks almost all the inconsistent bits as shown in green areas and it decreases the HD score to 0.007 compared with traditional HD score of 0.137. Similarly, frontal vs. off-angle image comparison shows lower HD score of 0.264 than traditional method with 0.423 HD. Compared with the traditional method result shown in **Fig. 2**(c), we observe that fragile bits image excludes half of the inconsistent bits between frontal and off-angle images as shown in **Fig. 3**(c).

IV. Off-angle Iris Dataset

We tested the proposed fragile bit method for off-angle iris images with a dataset of 8473 frontal and off-angle iris images from left eye of 78 different subjects. All images captured with an IDS-UI-3240ML-NIR camera, a Navitar Zoom 7000 lens at 40mm focus and 5.6 f-stop, and a 720 nm high-pass filter under a 780 nm NIR light source. The camera moves horizontally on an rotational arm from -50° to +50° in angle and captures 10 images at every stop with a 10° step-size. During the image capture, subjects open their eyes and look a fixation point at 0° in angle. Frontal iris images are captured when camera is at 0° in angle and subjects look at directly to the camera. **Fig. 5** shows the data capture platform that used to take the off-angle iris images and captured sample off-angle iris images. In total, it captures 10 frontal and 100 off-angle images for each subject from 11 different gaze angles. Each captured original image has 1280x1024 pixels in a single grayscale channel. The iris diameter is around 410 pixels in a frontal image.

To find the pupil and sclera boundaries of iris images, we used edge orientation based off-angle iris segmentation algorithm [13] by fitting two ellipses. To minimize the errors in segmentation causing the high HD scores, two operators check the segmentation parameters and correct them manually if needed. In addition, we also segment the upper and lower eyelids using second degree polynomials as shown in **Fig. 5** (c-f). Before end of 2021, we will release the dataset and its segmentation parameters at [14] after finishing the ground-truthing. We developed our algorithms in MATLAB and run our codes on a DELL Precision workstation with 16 i9-9900K processor at 3.6GHz and 64GB memory.

V. Results and Discussion

We conducted three sets of experiments using our off-angle iris datasets. We first present the recognition performance of a traditional iris recognition algorithm for our off-angle iris dataset without using fragile bit masking. Second, we present the results for our proposed method using different edge detection methods

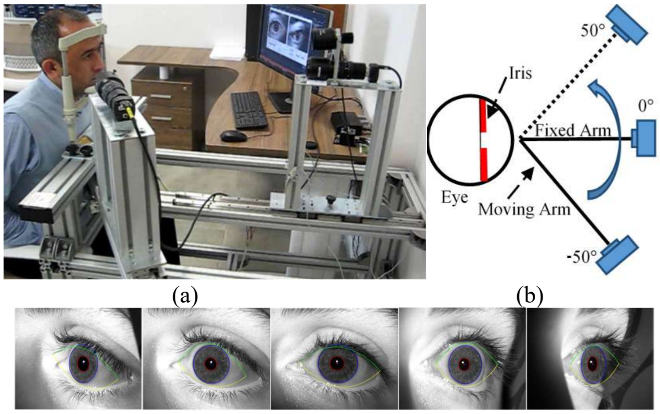


Fig. 5. (a) Data capture platform for off-angle iris images, (b) Illustration of off-angle iris data capture, example captured images from different gaze angles (c) -50º, (d) -30º, (e) 0º, (f) 30º, (g) 50º in angle.

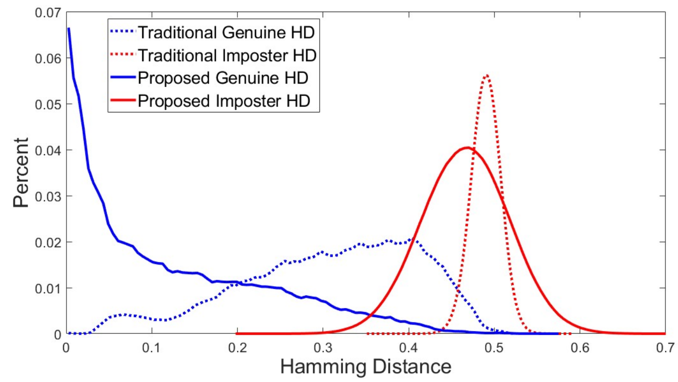


Fig. 4. Distribution of Hamming distance scores for off-angle images using traditional and proposed methods. The solid lines represent genuine comparisons and the dotted lines for imposters.

and various dilation sizes. Finally, we compare the performance of proposed method with a well-known fragile bit masking method in literature [6].

To compare the recognition performance of proposed fragile bit masking method, we first adopt a Gabor based state-of-the-art iris recognition algorithm [1] as a baseline result without using fragile bit masking. To generate the iris codes, we applied the OSIRIS phase-quadrant demodulation [12] on normalized images. It delivers an occlusion mask for eyelid occlusions and six iris codes at size of 64x512 for real and imaginary responses of three different Gabor filters. For our experiments, iris codes of only one frontal image per subject is stored in the database and the remaining frontal and off-angle images are used as the probes. To calculate the Hamming distance in traditional method, each probe image is compared with the images in the database using Eq. 1. Then, we repeat the same experiments for rest of the frontal images by placing them into the gallery one by one. Therefore, over 6.2 million pairs of comparisons (gallery vs. probes) are performed for each set of experiments.

Fig. 4 shows the distributions of genuine and imposter comparisons (marked with red lines) between the off-angle images using traditional methods. The genuine plots represent the comparisons of images from the same subjects and the imposters comparisons are between images of two different subjects. For the traditional method without using fragile bit concept, the HD scores in genuine class (shown with red solid line) ranges from 0.01 to 0.5268 with an average of 0.3082 and a standard deviation of 0.1024. The score of the imposter comparisons (marked with red dotted line) changes from 0.35 to 0.59 with a mean value of 0.49 and a standard deviation of 0.0173. Due to the gaze angle difference between probe and gallery images, it is observed that the traditional method measures the genuine HD scores of some images larger than imposter comparisons and their distributions are overlaps. Therefore, traditional method produces false match and false reject errors.

Second, we run the same experiment with the proposed fragile bit masking method and calculate the Hamming distance scores using Eq. 3. As shown in **Fig. 4** with a solid blue line, proposed method shifted the genuine HD histogram to the left

TABLE I
COMPARISON OF TRADITIONAL AND PROPOSED METHODS USING MEAN AND STANDARD DEVIATION OF GENUINE AND IMPOSTER DISTRIBUTIONS

	Genuine Comparison		Imposter Comparison	
	Mean	Std	Mean	Std
Traditional Method	0.3082	0.1024	0.4900	0.0173
Proposed Method	0.1244	0.1110	0.4662	0.0512

that has an average of 0.1244 and a standard deviation as 0.111. Also, the histogram of the imposter comparisons slightly shifted left (marked with dotted blue line) with a mean value of 0.4662 and a standard deviation of 0.0572 because fragile bit masking decreases the number of bits in each comparison. **Table I** summaries the mean and standard deviation values in genuine and imposter comparisons for traditional and proposed methods. We observed that proposed method decreased the mean of genuine class by 60% while the mean of imposter class only decreased by 4.8%. However, its standard deviation is almost tripled because of the decrement in the number of compared bits in the proposed fragile bit masking method.

To investigate more on how the fragile bit masking addressing the effect of gaze angles in off-angle iris images, we also calculate the average Hamming distance scores in genuine comparisons for each gaze angle combinations of gallery and probe images. In this experiment, we only include images from a specific angle in gallery and tested with images from another specific angles. **Fig. 6**(a-b) presents the average Hamming distance scores for traditional and proposed methods, respectively where x-axis refers to the gaze angle of probe image and y-axis is for angles of the gallery images. For example, comparison of frontal (0° in angle) and 40° off-angle images gives an average HD score of 0.365 in traditional method. Using proposed method, the mean score drops to 0.167. Therefore, proposed method provides 54% improvement in the genuine Hamming distance scores. Expectedly, the average HD scores increase as the difference between the compared images increases. Diagonal axis shows the smallest HD scores for images with the same gaze angle in both methods. **Fig. 6**(c) presents the percentage of genuine Hamming distance scores improvements for each gaze angle combinations. The proposed

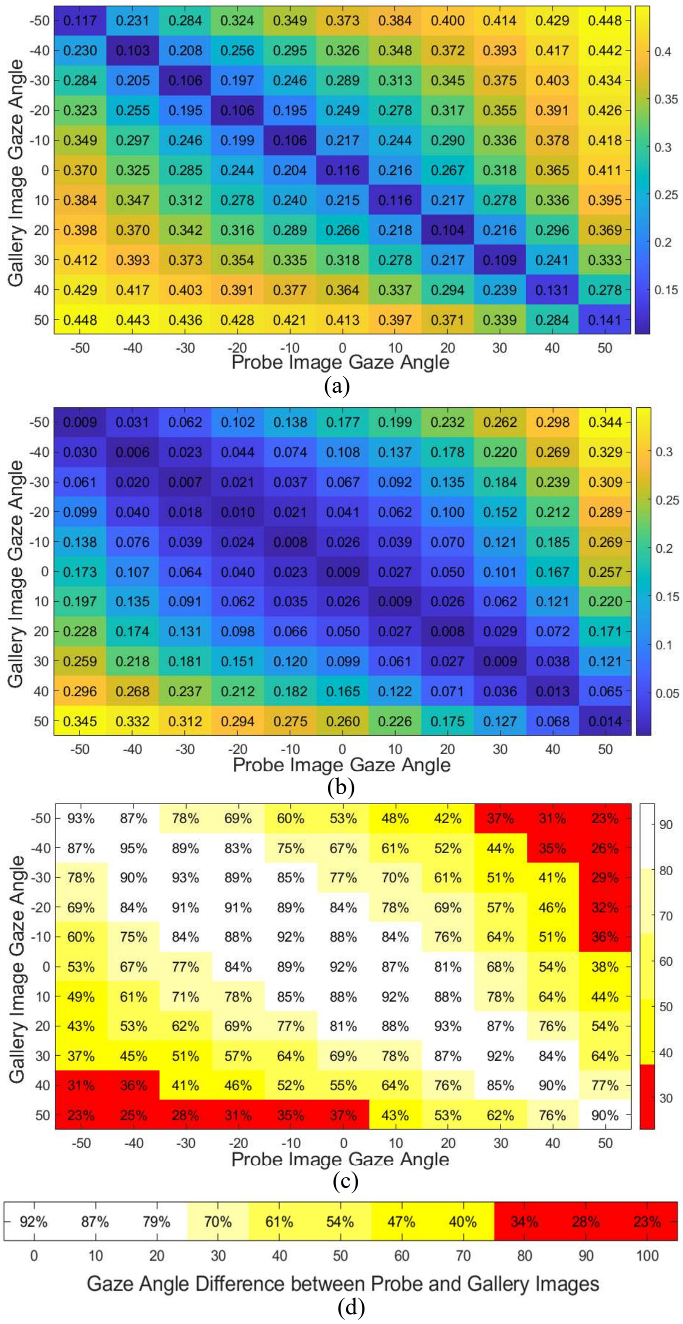


Fig. 6. The average genuine Hamming distance scores between gallery and probe images from different gaze angles using (a) the traditional method and (b) the proposed method. The improvement percentage of genuine Hamming distance scores using proposed method compared with traditional method for (c) each gaze angle combinations, and (d) the gaze angle differences between compared images.

method lowers the genuine HD score for all gaze combinations ranging from 95% to 23%. We observed the high improvement percentages for the diagonal axes when the probe and gallery image have same gaze angle such as -50° vs -50° or 0° vs 0°. As moving of the diagonal, the improvement decreases because the gaze angle difference increases. We calculated the average genuine HD score improvements for each gaze angle difference between probe and gallery images and show them in **Fig. 6**(d).

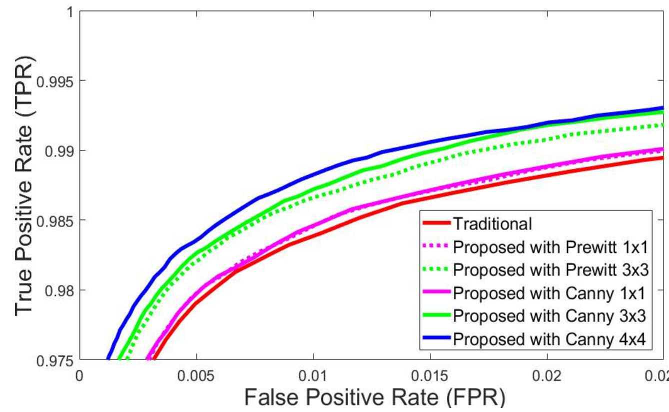


Fig. 7. Performance analysis using ROC curves for traditional iris recognition method and proposed fragile bit masking method using different edge detection techniques (Canny and Prewitt) and various dilation structuring elements sizes (1x1, 3x3, and 4x4).

We observe that the improvement for smaller gaze difference is higher than large gaze differences. When compared images have the similar gaze angles, the image distortions affect them similarly such as cornea refracts the light same way and limbus occludes the iris same amount. Fragile bit masking can eliminate these small variations in the iris codes. However, if the gaze difference is extremely high such as 100° (images at 50° vs -50°), the proposed method still helps but its improvement is limited as 23%. In case of large gaze difference, the dilation amount in fragile bit mask generation can be increased to enlarge the masked area as a potential solution.

To compare the recognition performance of traditional and proposed methods, we also plot the Receiver operating characteristic (ROC) curves and calculated equal error rates (EER) as performance metrics. Since the proposed method is based on edge detection and dilation operation, we test our method using different edge detection techniques, including Canny and Prewitt edge detectors and various dilation structuring elements sizes, including 1x1, 3x3, and 4x4. As seen in **Fig. 7**, it is observed that Canny edge detection shows slightly better performance than Prewitt. In addition, when a bigger size of the dilation operation is used to enlarge the fragile bit masks, the recognition performance increases where their ROC curves shifted to upper left corner. Among others, Canny-based fragile bit mask detection with 4x4 dilation operation (solid blue line) shows the best performance with an EER of 1.12%. Traditional method (solid red line) showed a lower performance with 1.38% EER score than proposed method. Therefore, elimination of fragile bits in off-angle iris recognition shows the performance improvement compared with the traditional iris recognition.

Last, we compared the recognition performance of our proposed method with a well-known fragile bit masking method [5]. Hollingsworth et. al masked the filter responses near the axes of complex plane. To detect those bits, they first sorted the filter responses in real and imaginary Gabor filter outputs and find the corresponding bits that are in the lower quartile of numbers. We generate the fragile bit masks using their definition and compare them with our proposed method

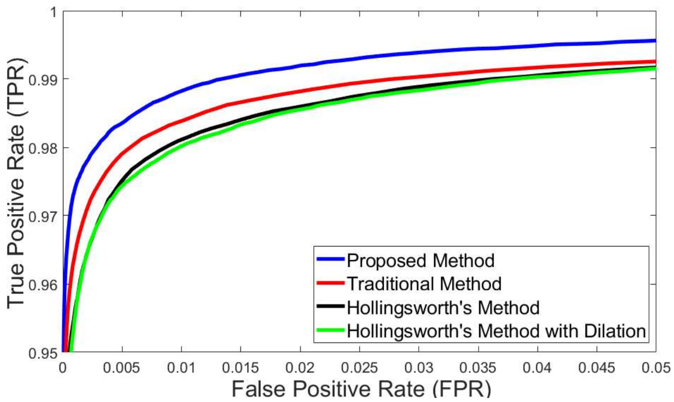


Fig. 8. ROC curves for performance comparison of proposed fragile bit masking method using Canny edge detector and 4x4 dilation with traditional iris recognition and a well-known fragile bits masking (Hollingsworth et. al [5]) with/without dilation.

using Canny edge detector with 4x4 dilation. For fair comparison, we also enlarge their fragile bit masks with a 4x4 dilation operation as another experiment. **Fig. 8** plots the ROC curves for the proposed method with blue line, traditional method with red line, Hollingsworth's method with black line, and Hollingsworth's method using dilation with green line. We observed that proposed method shows the best performance compared with others. Instead of improving the recognition performance, Hollingsworth's fragile bit masking method showed a lower accuracy than traditional method. In addition, the dilation of their fragile bit masks could not help to improve the performance. The EER scores for Hollingsworth's method with/without dilation are 1.61% and 1.60%, respectively. Compared with traditional iris recognition method and Hollingsworth's fragile bits masking method, the proposed fragile bit masking method using Canny edge detector with dilation shows superior performance for the off-angle iris recognition. In addition, since our proposed method detect the fragile bits using edge detection and dilation on iris codes, it can be easily adopted into the existing algorithms and datasets without the requirement of recapturing the iris images again. However, Hollingsworth's method needs the filter responses on normalized images to detect the fragile bits where existing systems store only iris codes in their database not normalized images. Therefore, the proposed method is compatible with the exist iris recognition systems and databases and helpful to improve the recognition performance for off-angle iris images.

VI. Conclusion

This study proposed a new fragile bit detection method in iris codes using edge detection and dilation and masking them in Hamming distance calculation to improve the recognition performance of off-angle iris images. We compared the proposed method with a traditional iris recognition algorithm and a well-known fragile bit masking method. We also investigated different edge detectors and various dilation sizes for the proposed fragile bit masking method. Based on the experimental results, proposed method improved recognition performance for off-angle iris images compared with traditional methods. Dilating the fragile bits also helps to eliminate the texture distortion due to the gaze angle difference between compared images.

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