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Feature-domain super-resolution for iris recognition ☆

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ABSTRACT

Uncooperative iris identification systems at a distance suffer from poor resolution of the acquired iris images, which significantly degrades iris recognition performance. Super-resolution techniques have been employed to enhance the resolution of iris images and improve the recognition performance. However, most existing super-resolution approaches proposed for the iris biometric super-resolve pixel intensity values, rather than the actual features used for recognition. This paper thoroughly investigates transferring super-resolution of iris images from the intensity domain to the feature domain. By directly super-resolving only the features essential for recognition, and by incorporating domain specific information from iris models, improved recognition performance compared to pixel domain super-resolution can be achieved. A framework for applying super-resolution to nonlinear features in the feature-domain is proposed. Based on this framework, a novel feature-domain super-resolution approach for the iris biometric employing 2D Gabor phase-quadrant features is proposed. The approach is shown to outperform its pixel domain counterpart, as well as other feature domain super-resolution approaches and fusion techniques.

1. Introduction

Biometric systems enable the automatic identification of individuals based on their physiological and behavioural characteristics such as face, fingerprint, palmprint, gait, iris, retina, and voice. Among the biometrics, the iris has been shown to be one of the most accurate traits for human identification due to its stability and high degree of freedom in texture [1,2]. Most existing iris recognition systems require users to present their iris to a camera at close distance (less than 0.6 m), to ensure images of sufficient quality are captured. The research community is interested in enabling iris recognition to be conducted in less constrained environments, such as when the subject is moving and at a distance. The two most significant problems when performing iris recognition at a distance are pixel resolution (i.e. the number of pixels in the iris region) and quality variation of the captured images [3].

Super-resolution techniques have previously been employed to address the low resolution problems of imaging systems [4]. There are two differing super-resolution approaches: reconstruction-based and learning-based. Reconstruction-based approaches such as [5–12] fuse the sub-pixel shifts among multiple low resolution images to obtain an improved resolution image. Alternatively, learning-based approaches model high-resolution training images and learn prior knowledge to constrain the super-resolution process [4].

Recently, super-resolution techniques have been applied to biometric systems. A number of super-resolution techniques have been successfully developed for face [13–17] and iris [18–21]. Kwang et al. [19] propose a learning-based super-resolution method using multiple MLPs (multi-layer perceptrons). The middle and high frequency components of a low resolution iris image are restored from the trained neural network architecture. Huang et al. [20] propose another learning-based method utilising a CSF (Circular Symmetric Filter). Their algorithm predicts the prior relation between iris feature information of different bands and incorporates this into the process of iris image enhancement. From a reconstruction perspective, Fahmy [18] proposed a reconstruction-based super-resolution technique to restore multiple low-resolution iris frames captured at a distance of 3 feet. Nguyen Thanh et al. [21] proposed to incorporate quality metrics into the super-resolution process to improve performance by assigning better quality frames a higher weight when fusing multiple low resolution images. Nguyen Thanh et al. [21] employs an exponential fusion scheme to estimate the high-resolution image from the low-resolution image sequence.

One main concern raised by both Gunturk et al. [22] and Nguyen et al. [23] is how to apply super-resolution for a specific biometric modality effectively to improve recognition performance, rather than visual clarity. Two issues have been raised:

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- The aim of applying super-resolution to biometrics is not for visual enhancement, but to improve recognition performance. Most existing super-resolution approaches are designed to produce visual enhancement. *If recognition improvement is desired, why do we not focus on super-resolving only items essential for recognition?*
- Each biometric modality has its own characteristics. Most existing super-resolution approaches for biometrics are general-scene super-resolution approaches. *Can any specific information from biometric models be exploited to improve super-resolution performance?*

Based on these concerns, feature-domain super-resolution techniques have been proposed for face [22,24] and iris [23] to improve recognition performance. These approaches no longer super-resolve images in the pixel-domain, but super-resolve the extracted features that are used for classification in the feature-domain, and the super-resolution output (a super-resolved feature vector) is directly employed for recognition. Different linear features including Principle Component Analysis (PCA) [22,23] and Tensor Face [24] have been investigated to improve the respective biometric modalities. These features are super-resolved to increase the resolution using a maximum a posteriori estimation approach. Specific knowledge of face and iris models are incorporated in the form of prior probabilities to constrain the super-resolution process, to make it robust to noise and segmentation errors. These approaches have been shown to outperform pixel-domain super-resolution approaches for face and iris recognition.

However, for the specific case of the iris biometric, the 2D Gabor wavelet has been shown to be one of the most effective encoding techniques since it achieves the best trade-off in both spatial and spectral resolution [25,26]. The major challenge that prevents feature-domain super-resolution from being successfully applied to the 2D Gabor phase-quadrant encoding technique is the non-linear nature of the encoding technique.

The existing feature domain super-resolution frameworks of [22–24] are unable to super-resolve non-linear features, and are thus not suitable for use with the 2D Gabor wavelet features. To further improve the performance of feature-based super-resolution for iris recognition, we seek to provide a new feature-domain super-resolution framework to overcome the non-linearity of 2D Gabor wavelet features. Using the proposed framework, a novel feature-domain super-resolution approach using 2D Gabor wavelets and the iris biometric is proposed. We show that the proposed approach outperforms the unenhanced features, the pixel domain super-resolution equivalent, as well as other existing feature domain super-resolution and fusion techniques. It should be noted that the proposed framework can also be applied to other non-linear features and other biometrics.

The remainder of this paper is organised as follows: a framework for applying feature-domain super-resolution with nonlinear features is investigated in Section 2; Section 3 describes the proposed feature-domain super-resolution approach for iris images; Section 4 describes the approach to estimate initial parameters of the estimation; Section 5 presents the experimental results; and the paper is concluded in Section 6.

2. Non-linear features for feature-domain super-resolution

Linear encoding techniques such as PCA and LDA have been investigated for feature-domain super-resolution for iris [23] and face [22]. A PCA encoding technique seeks to project an image onto dimensions which best reconstruct the original data. Alternatively, a LDA encoding technique projects an image onto dimensions which maximise the separation of classes. Both methods capitalise on the global trend in the training data to represent each iris image as a linear superposition of fundamental functions (eigenface/eigeniris for PCA and fisherface/fisheriris for LDA). These techniques have been employed to conduct pioneering experiments on iris feature-domain super-resolution [23], and face feature-domain super-resolution [22]. The benefit of using PCA and LDA features is their linear superposition property, which simplifies the estimation of the high resolution features. However, these global features lose spatial information since they decompose the 2D image into a 1D vector [27].

For the iris biometric, the phase-quadrant encoding technique based on 2D Gabor wavelets has been shown to extract the most discriminant features of an iris [2,28]. The advantages of this encoding technique are rapid matching, a binomial impostor distribution and a predictable false acceptance rate [26]. Furthermore, 2D Gabor wavelets have also been shown to be highly effective for face recognition tasks [29]. Hence, employing these coarse phase features rather than PCA or LDA within feature-domain super-resolution has the potential to further improve recognition performance, advancing the state-of-the-art biometric systems. Despite these advantages, the non-linear nature of the encoding technique has prevented it from being investigated for feature-domain super-resolution. The non-linearity (due to the use of phase-quadrant encoding) makes the estimation of a high resolution feature from multiple low resolution features very challenging [23], as it makes the relationship between the multiple low resolution features and the high resolution feature very difficult to establish. In the remainder of this section, we analyse this encoding technique to discuss how feature-domain super-resolution can be applied using the non-linear 2D Gabor features.

A brief description of the conventional iris encoding technique [2] is illustrated in Fig. 1. Prior to feature extraction, an eye image is segmented to locate and extract the iris region. Two circles are employed to approximate the pupillary and limbus boundaries of the iris region. This region is normalised to a fixed size so that it can be used for comparison. The normalisation process uses a rubber-sheet model to transform the iris texture from Cartesian to polar coordinates. The remapping of the iris image $I(x,y)$ from raw Cartesian coordinates (x,y) to the dimensionless polar coordinates (r,θ) can be represented as,

$$I(x(r,\theta),y(r,\theta)) \rightarrow I(r,\theta), \quad (1)$$

where r is on the unit interval $[0,1]$, θ is an angle in the range $[0,2\pi]$, $x(r,\theta)$ and $y(r,\theta)$ are defined as a linear combination of both the set of pupillary boundary points $(x_p(\theta),y_p(\theta))$ and the set of limbus boundary points $(x_s(\theta),y_s(\theta))$, such that,

$$\begin{aligned} x(r,\theta) &= (1-r)x_p(\theta) + rx_s(\theta), \\ y(r,\theta) &= (1-r)y_p(\theta) + ry_s(\theta). \end{aligned} \quad (2)$$

Each normalised iris is then demodulated to extract the phase information using quadrature 2D Gabor wavelets,

$$h_{Re,Im} = sign_{Re,Im}\left(\int_\rho \int_\phi I(\rho,\phi)e^{-i\omega(\theta_0-\phi)}e^{-((r_0-\rho)^2/\alpha^2+(\theta_0-\phi)^2/\beta^2)}\rho d\rho d\phi\right), \quad (3)$$

where $h_{Re,Im}$ can be regarded as a complex-value component whose real and imaginary parts are either 1 or 0 depending on the sign of the 2D integral; $I(\rho,\phi)$ is the normalised iris image; α and β are the multi-scale 2D wavelet size parameters; and (r_0,θ_0) represents the two dimensions of the normalised iris image. Only phase information is used for recognition because amplitude information is not discriminant, and depends on extraneous factors such as imaging contrast, illumination and camera gain [2]. Altogether, 2048 phase bits establish the *IrisCode*.