Use of optical vortices for the compression of fingerprint recognition systems

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Abstract. In this article, an algorithm is presented for the processing and verification of fingerprints by analyzing optical vortices present in the orientation of the fringes of the fingerprint. The algorithm presents a compression factor of 1200, but is highly susceptible to the presence of noise.

1. Introduction

It is well known that fingerprint verification is one of the most popular and broadly used biometric technologies. Because of its success, there exists large databases that contain the information of millions of users [1]. Therefore, methods and algorithms that yield high compression factors whilst allowing the reliable recognition of a person's identity are required [2]. Our work was motivated by the work of Larkin and Fletcher [2], who obtained useful information from the amplitude and phase of fingerprints using an holographic analysis framework. Minutiae location was shown to be related with phase singularities. After a revision of their work, we propose a similar yet different approach to reduce the information that needs to be stored, while reducing the number of calculations. We also detected problems in some of the steps required for phase demodulation, and we propose a way to omit this process.

2. Background

Larkin and Fletcher [2] developed a fingerprint analysis framework based on interferometry where fingerprint images are represented as holograms: $f(x, y) = a(x, y) + b(x, y)\cos(\psi(x, y))$. One of the common methods used for fingerprint classification and recognition consist on locating the minutiae of the fingerprint [3, 4]. Minutiae are characteristic details such as bifurcations, abrupt ends and loops. From interferometry, it is known that this details can be modeled as phase singularities, also called optical vortices, in the phase of the fringe pattern [2, 5].

The fringe pattern representation of the fingerprint image can be understood as the in-phase component of a complex optical field. Thus, for obtaining the desired phase, the quadrature component of the field is required. Larkin [6, 7], proposed an isotropic two-dimensional radial extension of the Hilbert transform for fringe patterns. The proposed transform, named the vortex operator, consists of multiplying the signal with a spiral phase kernel in the Fourier domain ($\mathcal{V}\{g(x, y)\} = \mathcal{F}^{-1}\{e^{i\theta(u,v)}\mathcal{F}\{g(x, y)\}\}$).

For a fringe pattern, Larkin [6] showed that the vortex operator obtained the quadrature of the field with an additional complex term, $\mathcal{V}\{b(x, y)\cos(\psi(x, y))\} \approx ie^{i\beta(x,y)}b(x, y)\sin(\psi(x, y)$.

The appearance of the direction field $\beta(x, y)$ is expected as direction estimation has been found to be important for fringe pattern and fingerprint processing [5]. However, this calculation isn't trivial: the direction of a local point in a fringe pattern cannot be usually differentiated from a π radian shifted version of itself, due to the even behavior of the cosine function. Thus, the direction map modulo 2π cannot be determined and only the orientation map modulo π can be estimated.

Larkin [8] proposed a method for orientation estimation through the use of a modified version of the vortex operator. This new operator, named the energy operator, was shown to be more robust to the presence of noise than other traditional gradient based methods, $\left(i\mathcal{V}\{g(x,y)\}\right)^2 + g(x,y)\mathcal{V}\{\mathcal{V}\{g(x,y)\}\} = b(x,y)^2 e^{2i\beta(x,y)}$. Although the direction map cannot be generally known, when the phase map is smooth and there are no singularities, some methods can be applied to recover the direction from the orientation [7, 5, 9].

Once obtained the direction map, the phase of the fringe pattern can be calculated from the in-phase and quadrature components. As discussed earlier, the phase contains singularities which are associated to minutiae in the fingerprint pattern. The detection of these singularities can be achieved by the residue theorem for phase unwrapping [9, 10], $\oint_C \nabla\psi(x,y) \cdot d\vec{l} = 2\pi \sum_{k=1}^{N} p_k$, where N is the number of singularities inside a close circuit C and $p_k \in \mathcal{Z}$ is the charge of the kth singularity. For fingerprints, the charge of the singularities are restricted to ± 1 as discussed in [2].

3. Use of phase for locating singularities

When the method described in the previous section was implemented, we found that direction estimation from the orientation map had a significant impact on the quality of the demodulated phase. Using the energy operator proposed in [8] and described in the previous section on a sample fingerprint image, the wrapped orientation map in Fig. (1a) was obtained. For direction recovery, the orientation was first unwrapped as shown in Fig. (1b). It can be seen that new structures appeared in the image: the horizontal streaks that go from within the fingerprint to the edges indicate the presence of vortices. It is known that phase singularities make the unwrapping process difficult, as the result becomes path dependent [9, 10]. The resulting phase map is shown in Fig. (1c) which presents streaks that induce a sign shift between the upper and the lower values. These streaks cause problems to locate the singularities in the phase map: false vortices are detected in the intersection between streaks and fringes.

There are some possible solutions to remove the sign shift caused by these singularities. In [10], a Helmholtz decomposition of the phase map in the "smooth" and "singular" components is proposed. However, as the singularities are detected using 2x2 pixel integration loops, there is uncertainty in the exact location of the vortex, which greatly increases the difficulty of the Helmholtz decomposition. Another solution is to use branch cuts [10] to minimize the effect of unbalanced singularities when the orientation is unwrapped. If the branch cuts could be oriented in such a way that the sign inverting streaks were parallel to the fringes, then the presence of false vortices would be avoided. Nevertheless, this would greatly increase the computational cost of phase unwrapping, and in some cases (e.g. the loop structure in the center of Fig. (1c)) it is impossible to design branch cuts that don't intersect with fingerprint fringes. An alternative approach is suggested after a number of observations of orientation and phase maps. The motivation for this approach is based upon the following question: **is there any relationship between the singularities present in the orientation map and those present in the phase map?**

4. Use of orientation for locating singularities

Once we evidenced the underlying problems of the fringe pattern's direction estimation, we analyzed the physical meaning of the singularities found in the orientation map. In [5] it is

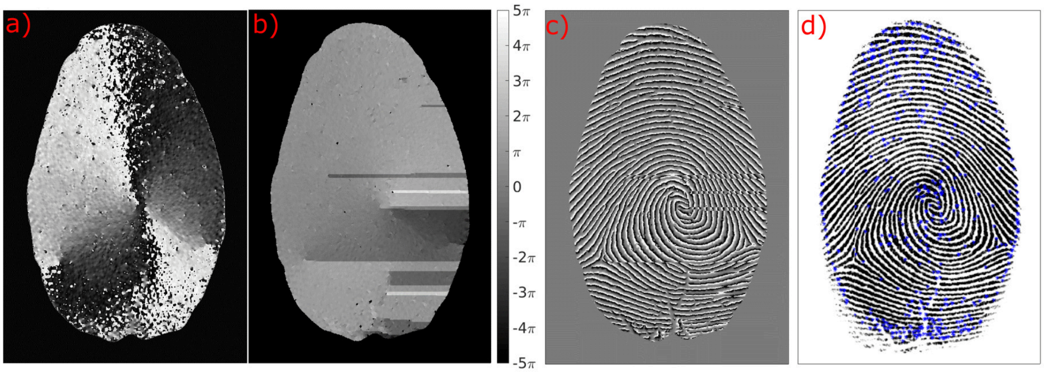

Figure 1: (a) Wrapped orientation map. (b) Unwrapped orientation map. (c) Demodulated phase from the unwrapped orientation. (d) Singularities found in the orientation map.

shown that certain fingerprint characteristics, such as deltas and loops, cause singularities in the local fringe orientation. As the phase map and its orientation are logically related, can the vortices in the orientation be assigned to fingerprint minutiae?

Vortex identification was performed over the orientation map, as shown in Fig. (1d). It can be seen that the location of the singularities (blue asterisks in the figure) in fact correspond to minutiae location in the fingerprint. Thus, knowledge of orientation suffices for minutiae identification. This results in a considerable reduction in complexity than the method presented by Larkin and Fletcher [2]. However, it was observed that only the positive charges of the singularities correspond to fingerprint minutiae. Therefore, although we no longer require to calculate the phase of the fringe pattern, we loose the information of the polarity of the singularities.

5. Proposed algorithm

In this section, we present an algorithm for minutiae detection for fingerprint recognition. Although the algorithm's structure is similar to the one proposed in [2], our approach has the objective of further compressing the information for recognition purposes and simplify the required calculations, but disregarding the reconstruction stage.

(i) **Step 1:** This step performs a first quality-enhancement preprocessing of the fingerprint image. This is required to remove the offset $(a(x,y))$. For our analysis, a simple bandpass filter proved to give good results, but more complex methods can be used [11].

(ii) **Step 2:** This step will separate the amplitude modulation and phase modulation components. We use the vortex operator on the filtered signal and take the magnitude of the output. This yields $b(x,y)|\sin(\psi(x,y))|$. If we take the arctangent of this signal with the output of **Step 1** we obtain an estimation of the phase $\psi(x,y)$ with a sign ambiguity due to the absolute value of the quadrature. However, as cosine is an even function, we can recover the in-phase component of the fringe pattern by taking the cosine of the estimation.

(iii) **Step 3:** In this step, we use the energy operator on the output of **Step 2**. As the magnitude of the input is 1, the output is just the complex signal related to the orientation $\exp(i2\beta(x,y))$. Taking the arctangent of the complex field, the orientation phase map $2\beta(x,y)$ is obtained.

(iv) **Step 4:** This step will locate the phase singularities present in the orientation map. For this, the residue theorem is used. As the orientation is assumed to be discretized in a matrix, the smallest possible closed circuit is a 2x2 pixel loop. For each position (m,n) in a matrix M, the presence of a singularity is given by: $\sum_{C_{2x2}} \nabla(2\beta(x,y)) \cdot \vec{dl} = p_k$.

(v) **Step 5:** Identify and save the (m, n) coordinates of the positive singularities. The relative positions of the vortices can be then used for fingerprint recognition [3, 4].

6. Discussion

In summary, the previous sections developed a method for locating singularities (associated with minutiae) in the orientation map of a fingerprint image. The input of the proposed algorithm is the scanned fingerprint image, and the output is the location of the positive singular values of the orientation map. Because of this, the information required to be stored for identification purposes is greatly compressed. The compression factor will depend on the number of singularities present in the orientation map and the maximum size of the image. The maximum compression factor we obtained was of 1200 for a 1200x800 pixels image, whilst the mean compression factor was approximately 500. However, there are some limitations and trade-offs that need to be taken into account. As discussed in the previous section, this work does not take into consideration the reconstruction of fingerprints, as only the minimum information possible is stored. This limits the possible uses but it is considered that applications that deal only on person verification and that are subject to heavily limited storage capacity could benefit from this method. Additionally, it was observed that noise and image quality had a very powerful effect on the results of the algorithm. Noisy images that present dirty or diffuse areas create false ridges that generate a high number of singularities. Also, the presence of pores is in some cases classified by the algorithm as short bifurcations and junctions of fringes, thus allocating a pair of singularities. It is suggested that this method is used along with high resolution fingerprint scanners: as the compression factor is high, this scanners can be used without the need to store a high amount of information.

7. Conclusion

This work examined the problems underlying the process of phase demodulation for locating the phase singularities associated with fingerprint minutiae. The presence of vortices in the fringe orientation induced a problematic phase unwrapping, which was observed with sign shifting streaks in the demodulated phase, that in turn originated false singularities. After analysis of the singularities in the orientation map, it was observed that these vortices corresponded as well with minutiae. It is proposed to calculate the vortex locations from the orientation map instead of the phase map. The resulting method and algorithm yield very high compression factors, but also evidenced to be greatly affected by noise and image quality.

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