Advanced Segmentation and Comparators for Iris Biometric Surveillance

by
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Abstract

Iris biometric systems recognize humans by their iris patterns, without the need of tokens or knowledge. So far, existing solutions have been limited to cooperative acquisition scenarios, but the cutting edge of research aims at providing new techniques and mechanisms to allow for uncooperative and less constraint iris image capture, facilitating iris recognition from surveillance data. When monitoring the behavior of people for security issues automatic identity determination is useful to prevent and prosecute criminal action.

In order to be able to process low quality input samples in real-time, including off-axis, defocused, motion-blurred images captured in visible wavelength or near infrared, sophisticated techniques are needed. This thesis presents the author's contributions with respect to two areas targeting the iris biometric surveillance problem: segmentation and comparators.

With respect to segmentation, a new combined face-and-eye detection technique more robust to changes in image conditions, and faster more robust iris segmentation models reducing search parameter space for localizing the textural area in the eye are presented. These methods facilitate the merger of visible wavelength dominated face and near infrared dominated iris recognition techniques.

While the majority of research in unconstraint iris recognition has concentrated on better segmentation models, as a new alternative to push forward recognition rates for the presented application scenario, the author has contributed refined comparators not only improving recognition rates but also exploiting the tradeoff between accuracy and speed for comparison.

Apart from these two main contribution branches also the compression of iris images and template protection mechanisms for enhanced privacy have been addressed.

Abstract (German)

Irisbiometriesysteme erkennen Menschen aufgrund ihrer Irismuster, ohne die Notwendigkeit von Token oder Wissen. Bisher waren existierende Lösungen limitiert auf kooperative Erfassungsszenarien, aber die Forschungsspitze erstrebt die Bereitstellung neuer Techniken und Mechanismen für unkooperative und weniger eingeschränkte Bilderfassung, um Iriserkennung aus Überwachungsdaten zu ermöglichen. Bei der Beobachtung des Verhaltens von Leuten aus Sicherheitsgründen ist die automatische Identitätsfeststellung nützlich, um kriminelle Handlungen zu verhindern und zu verfolgen.

Um Eingabebeispiele niedriger Qualität einschließlich ausserhalb der optischen Achse aufgenommener, defokussierter, bewegungsunscharfer Bilder im sichtbaren oder nahinfraroten Bereich in Echtzeit verarbeiten zu können, sind anspruchsvolle Techniken notwendig. Diese Doktorarbeit präsentiert die Beiträge des Autors bezüglich zweier Gebiete, welche das Irisbiometrie-Überwachungsproblem behandeln: Segmentierung und Komparatoren.

Bezüglich Segmentierung werden ein neues kombiniertes Gesicht-und-Auge Detektionsverfahren, welches robuster gegen Veränderungen in Bildkonditionen ist, sowie schnellere und robustere Irissegmentierungsmodelle vorgestellt, welche den Parameterraum reduzieren um die texturierte Fläche des Auges zu lokalisieren. Diese Methoden fördern die Verschmelzung von sichtbarer Wellenlänge dominierender Gesichts- und Nahinfrarot dominierender Iriserkennungstechniken.

Während sich der Großteil der Forschung in uneingeschränkter Iriserkennung auf bessere Segmentierungsmodelle konzentrierte, hat der Autor als neue Alternative Erkennungsraten für das präsentierte Anwendungsszenario zu verbessern verfeinerte Komparatoren beigetragen, welche nicht nur Erkennungsraten verbessern, sondern auch die Wechselbeziehung zwischen Genauigkeit und Geschwindigkeit für den Vergleich ausnutzen.

Neben diesen beiden Hauptbeitragszweigen wurden auch die Kompression von Irisbildern und Template-protection Verfahren für erhöhten Datenschutz untersucht.

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I would like to thank all people who were a source of inspiration and motivation throughout my studies and work at the University of Salzburg. I am deeply grateful to my advisor Andreas Uhl for his guidance and assistance throughout my PhD. Furthermore I greatly appreciate the inspiring discussions, interest and valuable hints of my colleagues and former colleagues of the Multimedia Signal Processing and Security Lab (WaveLab) at the University of Salzburg. In particular I would like to thank my co-workers and co-authors (in alphabetical order) Heinz Hofbauer, Mario Konrad and Christian Rathgeb. Finally, I would like to thank my family and friends for their endless love, support and encouragement.

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Salzburg, August 2012 *Peter Wild*

Contents

1. Introduction

This cumulative dissertation covers in detail my research work with respect to advanced segmentation and biometric comparators for iris biometric surveillance. According to Jain and Ross [30] we understand biometrics as the *"science of establishing the identity of an individual based on the physical, chemical or behavioral attributes of the person"*. Iris biometrics using patterns of the iris in human eyes for biometric authentication is a relatively young science, founded by L. Flom and A. Safir's concepts [19] and J. Daugman's realization of the first automated iris recognition system [13] (see also [57]). Surveillance is the *"close observation, especially of a suspected spy or criminal"* [43] and in context of this thesis refers to the unattended, possibly uncooperative, user-unaware capture of the modality in non-standard environments according to Wayman's [80] classification (see also [58]). This thesis is dedicated to the development of making iris recognition methods suitable for surveillance purposes, which has been a striving ongoing task in recent years involving many biometric research groups. Published research results included in this thesis are dividable into three categories: *fundamentals* listing surveys and overview reports with a special focus on iris preprocessing and compression, *iris segmentation* being probably the most critical (and difficult) task in iris biometric surveillance presenting new refined approaches to the eye detection and boundary localization problems, as well as *iris biometric comparators* targeting a refined comparison stage capable of tolerating distortions even more effectively, reducing the amount of comparisons or otherwise improving the comparison process. The collection of scientific publications reprinted in this thesis presents a recognized journal and conference articles as well as book chapters and a technical report related to the topic of the dissertation. Since the author has been involved as co-author in a large monograph on iris recognition [59], the introductory part of this thesis is realized in form of reprints of the book chapters [57, 60] introducing the reader to the topic. Whereas [59] also presents a unified and comprehensive presentation and discussion of content from most papers reprinted in this thesis, putting results into an even larger context, the author has decided to include the original research papers in this thesis in order to adhere to formal criteria and protect copyright-related interests.

The organization of this thesis is as follows: in this introductory chapter, all publications are discussed in detail, highlighting the authors' contribution classifying research results and giving guidance through the thesis. In Chapter 2 publications are listed in thematically sorted form. Chapter 3 concludes the work.

1.1. Fundamentals

Chapter [57] briefly introduces the human iris as a biometric identifier by giving a presentation of iris anatomy (see also [20]) and an overview of the historic milestones (most importantly, [19, 13]) in the short two decades of history in iris recognition. Furthermore, this chapter especially strives for giving detailed information on the distinctive properties of the iris making it an outstanding biometric modality when it comes to identification: high uniqueness, stability over years, and good collectability being a well protected internal organ.

In [60] the reader is introduced to the principle of operation of iris biometric systems covering in detail individual modules in the iris biometric processing chain. Different types of iris acquisition cameras following the classification in [79] are presented, with a strong focus on new surveillance-based stand-off portal (e.g., [66]) and hand-held (e.g., [35]) techniques, discussing the critical role of wavelength in the capture process. This chapter also reviews feature extraction techniques and introduces the reader to Hamming Distance (HD) based comparison in the two different *verification* and *identification* operation modes. Finally, typical performance measures of biometric systems are discussed.

In chapter [58] a systematic presentation of the state-of-the-art in iris recognition up to the year 2012 with respect to databases, performance challenges, literature, reference software, recognition performance, deployments and open issues is given. This chapter contributes to existing work in summarizing a large variety of different resources. Until now, reviews of the state-of-the-art in iris recognition have been rather dispersed in several different first-class studies (ITIRT [75], Daugman's UAE study [15], IRIS06 [2], IREX I-III [22, 67, 21]), in heterogeneous reference monographs [29, 37, 7], and also a variety of important single references (e.g., [12, 81, 14, 16]) or surveying articles reflecting the state-of-the-art at the time of release [5, 6].

Chapter [61] is a critical analysis of segmentation techniques with respect to more challenging recording conditions covering the large variety of different proposed techniques up to release including a systematic classification of approaches. In contrast to the well-known survey [5] it is solely dedicated to iris segmentation techniques covering also more recent approaches. The chapter distinguishes itself from [44, 45] in focusing not only on visible wavelength methods but on a broader range of techniques and from [46] in more exhaustively presenting different methods focusing on a presentation of the approaches rather than reported error rates (which are often hard to compare reliably, as some techniques have been found to be tuned to specific sensors or datasets [73]).

In particular for surveillance scenarios, where usually very large amounts of data have to be stored, compression of biometric data (as specified in ISO/IEC FDIS 19794-6) is a valuable means to reduce transmission and storage cost of images/videos, but may affect both, segmentation and recognition accuracy. Technical report [55] analyzes in detail the application of compression at various different stages in the iris biometric processing chain, i.e. at image acquisition, after segmentation using an ROI-encoded version, and after normalization using iris textures in "Faberge coordinates" [14]. This work augments existing studies [48, 28, 17] with respect to a systematic evaluation of application scenarios and highlights the critical role of segmentation in the processing chain.

Publications (sorted chronologically)

[57] C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 1 (The Human Iris as a Biometric Identifier), pages 3–6. Advances in Information Security. Springer, New York, 2012. To appear

[60] C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 2 (Iris Biometric Processing), pages 7–19. Advances in Information Security. Springer, New York, 2012. To appear

[58] C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 3 (State-of-the-Art in Iris Biometrics), pages 21–36. Advances in Information Security. Springer, New York, 2012. To appear

[61] C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 5 (Iris Segmentation Methodologies), pages 49–72. Advances in Information Security. Springer, New York, 2012. To appear

[55] C. Rathgeb, A. Uhl, and P. Wild. Evaluating the Impact of Iris Image Compression on Segmentation and Recognition Accuracy. Technical Report 2012-05, University of Salzburg, Department of Computer Sciences, 10 pages, July, 2012

1.2. Iris Segmentation

Not only compression, but also other quality degrading factors like uneven illumination, motion blur or defocus, as well as violations of quality assuring recording conditions, e.g. on-axis images, no eyeglasses, or assumptions on the recording wavelength (NIR versus VW), make segmentation the most challenging problem in iris recognition from surveillance data, supported by claims in [44] and also challenges [42, 65]. Therefore the segmentation problem is at the heart of iris biometric surveillance and has been thoroughly investigated. Contributive results of the author have concentrated on two problems: (1) reliable detection of eyes in facial images and (2) robust iris segmentation from challenging images adhering to the following constraints: (1) aiming at parameterless methods avoiding database-specific tuning; (2) real-time methods and; (3) methods able to solve the segmentation problem for both, near infrared (NIR) and visible wavelength (VW) data to support a merger and co-operation of traditional VW-operating surveillance-type cameras and specialized NIR-operating access control cameras.

Regarding the first problem of reliable detection of eyes in facial images regardless of the employed image type, [71] presents a new method enhancing individual detectors by employing Gaussians to learn a face model of detection responses of individual detectors. Existing (and potentially improving) single detectors dedicated to specific image types may be combined in a very generic way improving common detection capabilities by fusing the result not in a cascaded (as in AdaBoost [76, 77] or multi-stage facial feature detection [11]), but in parallel manner allowing for any type of face or face-part detector.

Having detected single eyes as face-parts, segmentation is the task of localizing inner (pupillary) and outer (limbic) boundaries in order to normalize iris images (intensity values are transformed into a doubly-dimensionless coordinate system proposed by Daugman [14] in order to tolerate pupil dilation). Since the dislocation of irides is able to cause mapping distortions which can hardly be corrected at later stages in the processing chain, this task is critical, especially for surveillance-type imagery, and usually quite time-consuming (in the literature, some proposed techniques require several seconds of processing time per image [44]). The papers [73, 72] target this problem by optimizing an iterative circular Hough Transform approach proposed initially by Cauchie *et al.* [8] following the idea of seeking a center point of multiple concentric rings by avoiding the search of a particular radius. The initially found center point may be used to simplify the segmentation problem by breaking it up into two stages, initial center detection and sequential boundary detection, assisting the localization of the second boundary by exploiting information of the localization result of the first curve. While [73] follows an approach based on a newly proposed *Ellipsopolar transform* (which is a modified polar transform mapping boundary-concentric ellipses to axis-parallel lines), [72] employs k-means clustering, Fourier-based trigonometry [17] and Pulling-and-Pushing [23] in the proposed multi-stage segmentation framework targeted at NIR and VW iris segmentation.

Publications (sorted chronologically)

[73] A. Uhl and P. Wild. Weighted Adaptive Hough and Ellipsopolar Transforms for Real-time Iris Segmentation. In *Proceedings of the 5th International Conference on Biometrics (ICB'12)*, 8 pages, New Delhi, India, March 29–April 1, 2012. IEEE

[71] A. Uhl and P. Wild. Combining Face with Face-Part Detectors under Gaussian Assumption. In A. Campilho and M. Kamel, editors, *Proceedings of the 9th International Conference on Image Analysis and Recognition (ICIAR'12)*, volume 7325 of *LNCS*, pages 80–89, Aveiro, Portugal, June 25–27, 2012. Springer. doi: 10.1007/978-3-642-31298-4_10

[72] A. Uhl and P. Wild. Multi-stage Visible Wavelength and Near Infrared Iris Segmentation Framework. In A. Campilho and M. Kamel, editors, *Proceedings of the 9th International Conference on Image Analysis and Recognition (ICIAR'12)*, volume 7325 of *LNCS*, pages 1–10, Aveiro, Portugal, June 25–27, 2012. Springer. doi: 10.1007/978-3-642-31298-4_1

1.3. Biometric Comparators

Having access to a normalized iris image, the feature extraction module generates a compact representation of the biometric signal (template), typically in binary form (iris-code). Traditional iris biometric systems employ the fractional HD at several different offsets (shifts) for comparison, in order to account for *rotational variance* and resulting misalignment (see [60]). As a completely different approach to target more challenging surveillance-type imagery (and the alignment problem during comparison), new iris biometric comparators have been introduced and assessed as part of this work. While commonly neglected in iris biometric systems so far [5], since the HD as proposed by Daugman facilitates fast and easily parallelizable comparison of binary templates, more sophisticated matching techniques yield a tradeoff between speed and accuracy, which can be exploited to (1) speed-up identification (screening) by fast rejection of unlikely matches [33, 50]; (2) achieve better alignment allowing for non-linear deformations at the cost of additional processing time [70]; (3) exploit even more information in the matching process by keeping track of not only the minimum HD over several bit shifts but also the maximum HD [54] or fitting a distribution to all obtained distances [56]; (4) combine multiple algorithms in a multi-algorithm fusion scenario achieving higher accuracy than each individual algorithm without the common drawbacks of increased template size or additional matching time [68, 52] and; (5) protect templates binding cryptographic keys based on bit reliability strengthening error correction capacities [53] compared to traditional fuzzy commitment schemes [32]. Augmenting these considerations, also the application of comparators on raw biometric data (ISO/IEC FDIS 19794-6) as well as normalized iris textures using common image quality metrics has been investigated, yielding a prospective application and knowledge-transfer between both research communities [25, 24]. These comparators may be classified as *alignment-optimized*, *reliability-based*, *fusion-based* and *Image domain* comparators.

1.3.1. Alignment-optimized Comparators

Alignment-optimized comparators concentrate on permitting higher degrees of freedom during the alignment process and/or exploit additional similarity information of binary iris-codes in order to be able to more robustly tolerate inaccurate segmentation or less restrictive recording conditions (off-axis, on-the-move images). Following [9, 10] assessing different binary vector similarity metrics, the folowing three comparators have been proposed.

The Levenshtein Distance (LD) [36] is a widely known distance measure, which can easily be computed using dynamic programming techniques [40]. In [70] a constrained version of the LD is proposed giving an upper limit on local misalignment - a rather typical and useful assumption for iris images (it is e.g., unlikely, that the iris image is rotated by more than 45 degrees) - in order to reduce the computational overhead. Theoretical considerations prove, that under the modifications given, the resulting algorithm lies in the same complexity class as HD with $O(n \cdot s)$ time and $O(n + s)$ space requirements, where n refers to the number of bits and s to the number of bit shifts. Empirical tests show rather small constants (on average 4-5 times slower).

Shifting score fusion [54] combines traditional minimum HD and maximum HD as a measure of systematic error in the alignment of genuine iris-code pairs. In contrast to other approaches [70, 52] this comes at almost no additional processing overhead and may easily be integrated into every HD-based comparator.

Following the idea in [54] of using more than just the best (minimum) HD score in the alignment process seeking for an optimal shift position, [56] uses even more information. In this case, the entire series of comparison scores is used to fit a Gaussian distribution (which is likely to represent an alignment over different bit-shifts in case of genuine pairs, since comparison scores typically improve until an optimal alignment). By combining the fitting with traditional minimum HD even higher accuracy can be achieved.

Publications (sorted chronologically)

[70] A. Uhl and P. Wild. Enhancing Iris Matching Using Levenshtein Distance with Alignment Constraints. In G. Bebis et al., editors, *Proceedings of the 6th International Symposium on Advances in Visual Computing (ISVC'10)*, volume 6453 of *LNCS*, pages 469–479, Las Vegas, NV, USA, November 29–December 1, 2010. Springer. doi: 10.1007/978-3-642-17289-2_45

[54] C. Rathgeb, A. Uhl, and P. Wild. Shifting Score Fusion: On Exploiting Shifting Variation in Iris Recognition. In *Proceedings of the 26th ACM Symposium On Applied Computing (SAC'11)*, pages 3–7, TaiChung, Taiwan, March 21–24, 2011. ACM. doi: 10.1145/1982185.1982187

[56] C. Rathgeb, A. Uhl, and P. Wild. Iris-Biometric Comparators: Exploiting Comparison Scores towards an Optimal Alignment under Gaussian Assumption. In *Proceedings of the 5th International Conference on Biometrics (ICB'12)*, 6 pages, New Delhi, India, March 29–April 1, 2012. IEEE

1.3.2. Reliability-based Comparison

Reliability-based comparators make use of a discovery of Hollingsworth *et al.* [26] in iris code bits not being uniformly distributed. By selecting user-specific "reliable" bits only, the accuracy of a biometric system can be increased. In contast to [26, 83] the proposed approaches [50, 53] do *not* rely on user-specific reliability masks, but employ global reliability. While at a first glance, this may be counter-productive, since noise masks should already capture "fragile" positions, indeed this approach has several benefits: (1) already very few bits (less than 10 percent) suffice, to get a rather good predictor of the final comparison score (which is not the case for noise masks, usually masking only small parts of an iris texture); (2) the approach makes noise masks preventible, which can save storage and processing time - permitting for more efficient comparison especially for large scale applications; (3) especially for surveillance-type imagery with likely occurring segmentation errors it may be desirable to be even more independent of noise masks.

In [50], for acceleration of biometric identification reliability masks are used to reject unlikely matches after having compared the most reliable parts of iris-codes. This technique is essentially a pre-screening approach, which in contrast to existing approaches [47, 82] does not relate to a specific number of pre-screening classes. For the target application of iris-biometric surveillance, such a comparator may be useful to quickly check for suspects in case there are huge amounts of samples (e.g. frames in video) and a large database the seeked identity is contained in, but only limited amounts of processing capabilities are available.

In contrast to classical biometric comparators, fuzzy commitment schemes (FCS) bind a cryptographic key to an iris-code. This way, biometric templates can be protected, which is useful in case biometric data is compromised (e.g., when stored on smart-card and the smart-card is stolen). Especially for the target application of biometric recognition at ATMs, a protection of templates stored on smart-cards is necessary to preserve privacy interests. Based on Juels and Wattenberg's framework [32], the comparator in [53] uses bit-reliability to re-arrange iris-codes of two different feature extraction algorithms in a FCS, in order to apply error correction capabilities more effectively (distributing reliable bits over the entire code).

Publications (sorted chronologically)

[50] C. Rathgeb, A. Uhl, and P. Wild. Incremental Iris Recognition: A Single-algorithm Serial Fusion Strategy to Optimize Time Complexity. In *Proceedings of the IEEE 4th International Conference on Biometrics: Theory, Applications, and Systems (BTAS'10)*, 6 pages, Washington, DC, USA, September 27–29, 2010. IEEE. doi: 10.1109/BTAS.2010.5634475

[53] C. Rathgeb, A. Uhl, and P. Wild. Reliability-balanced Feature Level Fusion for Fuzzy Commitment Scheme. In *Proceedings of the 1st International Joint Conference on Biometrics (IJCB'11)*, 7 pages, Washington, DC, USA, October 10–13, 2011. IEEE. doi: 10.1109/IJCB.2011.6117535

1.3.3. Comparators in the Image Domain

Biometric recognition from surveillance-type imagery is very challenging. For this reason, it is useful to avoid any information loss during the feature extraction process. In the typical iris biometric processing chain [60], feature extraction techniques are applied to simplify the comparison task and remove all "noise" from the captured biometric data, which can not be used for recognition. However, there is no "ideal" feature extraction technique available (otherwise comparison would be rather trivial, checking for equality). In some cases (e.g., forensic application) fast comparison may not be a main objective.

In [25] image quality metrics are applied directly to iris images as well as normalized iris textures. While traditional techniques like image metrics can not yet outperform classical feature vector-based techniques, results perform even better than expected using normalized input and are a prospective means for future forensic comparators operating in image domain, permitting a knowledge-transfer between quality metrics and biometric comparators and vice-versa (e.g. by obtaining insights why specific metrics perform better than others).

Image quality metrics can also successfully be combined as well as fused with classical biometric comparators, improving the total accuracy. Results in [24] illustrate the applicability of this approach. Nevertheless, experiments also highlight, that biometric fusion does not necessarily improve recognition (an effect claimed and proven by several authors [63]), and that comparators should assess complementary information to benefit from increased accuracy. This combination of biometric comparators may also be classified as a fusion-based technique.

Publications (sorted chronologically)

[25] H. Hofbauer, C. Rathgeb, A. Uhl, and P. Wild. Iris Recognition in Image Domain: Quality-metric based Comparators. In G. Bebis et al., editors, *Proceedings of the 8th International Symposium on Visual Computing (ISVC'12)*, volume 7432 of *LNCS*, pages 1–10, Crete, Greece, July 16–18, 2012. Springer

[24] H. Hofbauer, C. Rathgeb, A. Uhl, and P. Wild. Image Metric-based Biometric Comparators: A Supplement to Feature Vector-based Hamming Distance? In *Proceedings of the IEEE International Conference of the Biometrics Special Interest Group (BIOSIG'12)*, volume 196 of *LNI*, 5 pages, Darmstadt, Germany, September 6–7, 2012. GI. To appear

1.3.4. Fusion-based Approaches

Fusion-based comparators combine multiple comparators in order to achieve even higher accuracy. Comparators may operate on the same or different templates (feature vectors), thus represent multi-comparator or multi-(feature extractor-)algorithm fusion. While also multi-sensor, multi-sample, multi-biometric or multi-instance fusion scenarios are possible [63], the following comparators target the first two scenarios. The distinction between fusion-based and other presented comparators is not sharp, e.g. [24, 53, 54, 56] also incorporate fusion-based elements, but have been introduced in the respective sections.

Typically, fusion comes at additional processing and storage overhead. In [69] several different types of fusion rules in parallel and serial mode are evaluated (using scores from a hand-based biometric system), including a weighted assessment taking different strengths of comparators into consideration.

However, fusion schemes may optimize both, recognition accuracy and processing requirements at the same time: in [68], which has been the pioneering work to this type of comparators, especially [50, 33, 52], a new serial classifier combination technique is proposed, which does not only reduce potentially matching candidates at each stage, but accumulates comparison information. Borda count, highest rank and score sum are employed as rules in the serial combination process [64] and compared to parallel techniques. By defining the sequential order of comparators and the fixed dimensionality of each comparator a serial combination can be tuned to specific needs. While the comparator has been evaluated for scores from a hand-based biometric system, the framework may be applied to any type of comparison scores.

After generic considerations in [69, 68] serial combinations in [33] specifically target iris recognition schemes. By employing rotation-invariant pre-selection using a fast technique [18] and more accurate, but costly classical matching techniques [39] performing rotational alignment via bit shifts, at comparable accuracy large amounts of processing time can be saved.

In [52] not only processing time but also the increased template size is targeted: multiple classical feature extraction techniques are combined building a strong template of most consistent bits, following the technique in [50]. Again, a multi-biometric scheme performing better than each single technique at even less processing time and storage is obtained.

Paper [51] surveys iris-code based comparators including proposed techniques and combines bit-reliability based [49] techniques and shifting score fusion [54] to achieve an even better tradeoff between accuracy and computational demands (storage and cpu time).

Publications (sorted chronologically)

[68] A. Uhl and P. Wild. Parallel versus Serial Classifier Combination for Multibiometric Hand-Based Identification. In M. Tistarelli and M. Nixon, editors, *Proceedings of the 3rd International Conference on Biometrics (ICB'09)*, volume 5558 of *LNCS*, pages 950–959, Alghero, Italy, June 2–5, 2009. Springer. doi: 10.1007/978-3-642-01793-3_96

[69] A. Uhl and P. Wild. Single-sensor multi-instance fingerprint and eigenfinger recognition using (weighted) score combination methods. *International Journal on Biometrics*, 1(4):442–462, 2009. Inderscience. doi: 10.1504/IJBM.2009.027305

[33] M. Konrad, H. Stögner, A. Uhl, and P. Wild. Computationally efficient serial combination of rotation-invariant and rotation compensating iris recognition algorithms. In *Proceedings of the 5th International Conference on Computer Vision Theory and Applications (VISAPP'10)*, volume 1, pages 85–90, Angers, France, May 17–21, 2010. SciTePress

[52] C. Rathgeb, A. Uhl, and P. Wild. On Combining Selective Best Bits of Iris-Codes. In C. Vielhauer et al., editors, *Proceedings of the Biometrics and ID Management Workshop (BioID'11)*, volume 6583 of *LNCS*, pages 227–237, Brandenburg on the Havel, Germany, March 8–10, 2011. Springer. doi: 10.1007/978-3-642-19530-3_21

[51] C. Rathgeb, A. Uhl, and P. Wild. Iris-Biometric Comparators: Minimizing Trade-Offs Costs between Computational Performance and Recognition Accuracy. In *Proceedings of the 4th International Conference on Imaging for Crime Detection and Prevention (ICDP'11)*, 6 pages, London, UK, November 3–4, 2011. IET. doi: 10.1049/ic.2011.0110

2. Publications

This online version chapter presents hypertext links to the publications being part of this cumulative thesis (the original printed version of this thesis presents publications as originally published, reprinted with permission from the corresponding publishers). The original publications are available from the corresponding publishers.
The copyright of the original publications is held by the respective copyright holders, see the following copyright notices.

[55] Technical report at the Department of Computer Sciences, University of Salzburg, Austria (2012), available at http://www.cosy.sbg.ac.at/research/tr.html

Chapter 1
The Human Iris as a Biometric Identifier

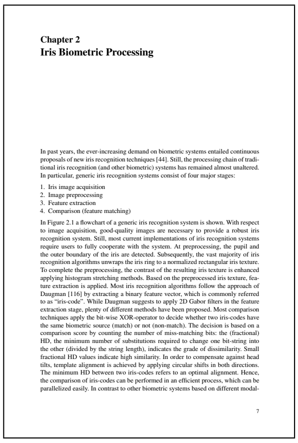
In 1984, a photographer named Steve McCurry traveled to Pakistan in order to document the ordeal of Afghanistan's refugees, orphaned during the Soviet Union's bombing of Afghanistan. In the refugee camp Nasir Bagh, which was a sea of tents, he took a photograph of a young girl approximately at the age of 13. McCurry's portrait turned out to capture emotion quite well and in June 1985 it ran on the cover of National Geographic. The girl's sea green eyes have captivated the world since then and because no one knew her name she became known as the "Afghan girl" [368].

In 2002, 17 year later, McCurry and National Geographic Television went back to Pakistan to search for the green-eyed girl. However, in the still standing Nasir Bagh refugee camp there were a number of women who came forward and identified themselves erroneously as the famous Afghan girl when they were shown her 1985 picture. In addition, a handful of young men falsely claimed the Afghan girl as their wife. The team was able to finally confirm her identity with the help of Prof. John Daugman's iris recognition software, which matched her iris patterns to those of the photograph with almost full certainty [48, 114]. Her name was Sharbat Gula, an estimated 30 year old woman, and she had not been photographed since then. The revealing of Sharbat Gula's identity manifested the strength of iris recognition technologies.

The term biometrics refers to "automated recognition of individuals based on their behavioral and biological characteristics" (ISO/IEC JTC1 SC37). Several physiological as well as behavioral biometric characteristics have been used [227] such as fingerprints, iris, face, hand, voice, gait, etc., depending on types of applications. Biometric traits are acquired applying adequate sensors and distinctive features are extracted to form a biometric template in the enrollment process. During verification (authentication process) or identification (identification can be handled as a sequence of verifications and screenings) the system processes another biometric measurement which is compared against the stored template(s) yielding acceptance or rejection. Iris biometrics refers to high confidence recognition of a person's identity by mathematical analysis of the random patterns that are visible within the iris of an eye from some distance [116], see Figure 1.1.

3

C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 1 (The Human Iris as a Biometric Identifier), pages 3–6. Advances in Information Security. Springer, New York, 2012. To appear.



Chapter 2
Iris Biometric Processing

In past years, the ever-increasing demand on biometric systems entailed continuous proposals of new iris recognition techniques [44]. Still, the processing chain of traditional iris recognition (and other biometric) systems has remained almost unaltered. In particular, generic iris recognition systems consist of four major stages:

1. Iris image acquisition
2. Image preprocessing
3. Feature extraction
4. Comparison (feature matching)

In Figure 2.1 a flowchart of a generic iris recognition system is shown. With respect to image acquisition, good-quality images are necessary to provide a robust iris recognition system. Still, most current implementations of iris recognition systems require users to fully cooperate with the system. At preprocessing, the pupil and the outer boundary of the iris are detected. Subsequently, the vast majority of iris recognition algorithms unwraps the iris ring to a normalized rectangular iris texture. To complete the preprocessing, the contrast of the resulting iris texture is enhanced applying histogram stretching methods. Based on the preprocessed iris texture, feature extraction is applied. Most iris recognition algorithms follow the approach of Daugman [116] by extracting a binary feature vector, which is commonly referred to as "iris-code". While Daugman suggests to apply 2D Gabor filters in the feature extraction stage, plenty of different methods have been proposed. Most comparison techniques apply the bit-wise XOR-operator to decide whether two iris-codes have the same biometric source (match) or not (non-match). The decision is based on a comparison score by counting the number of miss-matching bits: the (fractional) HD, the minimum number of substitutions required to change one bit-string into the other (divided by the string length), indicates the grade of dissimilarity. Small fractional HD values indicate high similarity. In order to compensate against head tilts, template alignment is achieved by applying circular shifts in both directions. The minimum HD between two iris-codes refers to an optimal alignment. Hence, the comparison of iris-codes can be performed in an efficient process, which can be parallelized easily. In contrast to other biometric systems based on different modal-

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C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 2 (Iris Biometric Processing), pages 7–19. Advances in Information Security. Springer, New York, 2012. To appear.

Chapter 3
State-of-the-Art in Iris Biometrics

Iris biometrics has received remarkable attention in the biometric community due to its unrivaled properties. Possessing epigenetic (not genetically determined) pattern information apart from color, the iris is widely employed as a biometric identifier because of its high *universality* (almost every person has the characteristic), *distinctiveness* (high discriminative power due to its entropy), *permanence* (stability except for pigmentation change over time) and *performance* (accuracy and speed). While according to the classification by Jain *et al.* in 2004 [229] there are other modalities with better *collectability* (the characteristic can well be measured), *acceptability* (people are willing to provide the characteristic), and *circumvention* (how easy the system can be fooled) properties, a lot of research effort has been invested to improve iris recognition with respect to these biometric properties. Typically, a good way to find a suitable biometric modality for a target application is to formulate conditions according to the characteristics. Wayman [575] classifies applications in a binary manner according to *cooperativity* (users are required to cooperate with the system), *user-awareness* (ouvert vs. covert acquisition), *habituation* (usability of the system), *attendance* (presence of operators), *standard environment* (indoors vs. outdoors), *publicity* (whether the system is open to public users), and *biometric data exchange* (being open or closed to exchange with other systems). Apart from the mainstream of cooperative, habituated, attended, indoor, private and closed applications, iris research has focused on non-cooperative, covert, unattended and outdoor applications, as well as approaches to facilitate iris biometric data exchange by conducting several challenges in the past, which are discussed in detail in Section 3.2. like the Noisy Iris Challenge Evaluation (NICE) [483], Multiple Biometric Grand Challenge (MBGC) [374] or Iris Challenge Evaluation (ICE) [372].

The world's largest biometric deployment, the Aadhaar project [548] by the Unique Identification Authority of India employs iris and fingerprints in a multi-biometric configuration to issue a unique identification number to each Indian resident launched in 2009. It has affirmed that iris biometrics exhibits excellent performance with its rapidly attenuating tails of the impostor score distribution: in a recent report [549] failure-to-enroll rates as low as 0.14%, false positive identification rates as low as 0.057% and false negative identification rates of 0.035% were reported for

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C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 3 (State-of-the-Art in Iris Biometrics), pages 21–36. Advances in Information Security. Springer, New York, 2012. To appear.


Chapter 5
Iris Segmentation Methodologies

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http://dx.doi.org/10.1007/978-3-642-31298-4_10


Combining Face with Face-Part Detectors under Gaussian Assumption*

Andreas Uhl and Peter Wild


Weighted Adaptive Hough and Ellipsopolar Transforms for Real-time Iris Segmentation

Andreas Uhl and Peter Wild*

A. Uhl and P. Wild. Weighted Adaptive Hough and Ellipsopolar Transforms for Real-time Iris Segmentation. In *Proceedings of the 5th International Conference on Biometrics (ICB'12)*, 8 pages, New Delhi, India, March 29–April 1, 2012.

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http://dx.doi.org/10.1007/978-3-642-31298-4_1

Multi-stage Visible Wavelength and Near Infrared Iris Segmentation Framework*

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Abstract. This paper presents a multi-stage iris segmentation framework for the localization of pupillary and limbic boundaries of human eyes. Instead of applying time-consuming exhaustive search approaches, like traditional circular Hough Transform or Daugman's integrodifferential operator, an iterative approach is used. By decoupling coarse center detection and fine boundary localization, faster processing and modular design can be achieved. This alleviates more sophisticated quality control and feedback during the segmentation process. By avoiding database-specific optimizations, this work aims at supporting different sensors and light spectra, i.e. Visible Wavelength and Near Infrared, without parameter tuning. The system is evaluated by using multiple open iris databases and it is compared to existing classical approaches.

Keywords: Iris biometrics, segmentation, preprocessing.

1 Introduction

Iris recognition uses patterns of the iris of an individual's eye for human identification and is considered to be one of the most accurate biometric modalities [2]. Traditional iris processing following Daugman's approach [5] extracts binary features after mapping the textural area between inner pupillary and outer limbic boundary into a doubly dimensionless representation. In this model, pixels are identified by their angular position and shift from pupillary to limbic boundary, see Fig. 1. This way, different pupil dilation caused by varying illumination conditions can largely be tolerated. Early segmentation techniques simply employed circular Hough Transform [17] to find a parameterization of the boundaries needed for the mapping process. However, iris images captured under more realistic, unsurveilled conditions cause problems. Noisy artefacts caused by blur, reflections, occlusions, and most notably oblique viewing angles may lead to severe segmentation errors. If such errors occur, subsequent recognition is almost impossible. Since iris segmentation is susceptible to poor image quality, efficient and fast segmentation of iris images is still an open research question [13].

While most proposed iris segmentation techniques (see [2] for a survey) follow holistic approaches optimizing the parameters for a more-or-less simple (circular,

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Parallel versus Serial Classifier Combination for Multibiometric Hand-Based Identification

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Abstract. This paper presents an approach for optimizing both recognition and processing performance of a biometric system in identification mode. Multibiometric techniques facilitate bridging the gap between desired performance and current unimodal recognition rates. However, traditional parallel classifier combination techniques, such as Score sum, Borda count and Highest rank, cause further processing overhead, as they require a matching of the extracted sample with each template of the system for each feature. We examine a framework of serial combination techniques, which exploits ranking capabilities of individual features by reducing the set of possible matching candidates at each iteration, and we compare its performance with parallel schemes. Using this technique, both a reduction of misclassification and processing time in identification mode will be shown to be feasible for a single-sensor hand-based biometric system.

Key words: multibiometrics, serial combination, hand biometrics

1 Introduction

Recently, a number of biometric systems have exploited advantages of multi-instance and multi-algorithm approaches to biometric recognition based on single-sensor input. In particular, such systems benefit of increased matching accuracy, more difficult biometric attacks, reduced enrollment errors in case of failures to extract single biometric traits and, finally, a less complex acquisition procedure [1–3]. For single-sensor fusion of iris and face a combined feature achieved 99.75% Genuine Acceptance Rate (GAR) compared to 97.35% GAR for face and 95.42% GAR for iris at 0.1% False Acceptance Rate (FAR) in [1]. A similar result was obtained for fusion of hand-based modalities with reported perfect classification compared to 91.5% GAR at 0.01% FAR for palmprints only and 95-99.9% GAR for individual fingers in [2] and good separation with 0.08% Total Error Rate (TER) compared to 0.24% TER for the best single feature (Minutiae) in [3]. All these studies combined matching scores by employing min-max score normalization and (weighted) sum of scores. While this technique seems to be a good choice outperforming many other alternatives [4, 5], processing time requirements are not optimized.

In a system with m biometric matchers M_i, $1 \leq i \leq m$ in identification mode, each sample B is matched against the whole system database $D =$

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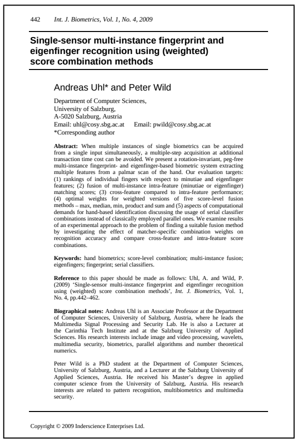

442 *Int. J. Biometrics, Vol. 1, No. 4, 2009*

Single-sensor multi-instance fingerprint and eigenfinger recognition using (weighted) score combination methods

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Abstract: When multiple instances of single biometrics can be acquired from a single input simultaneously, a multiple-step acquisition at additional transaction time cost can be avoided. We present a rotation-invariant, peg-free multi-instance fingerprint- and eigenfinger-based biometric system extracting multiple features from a palmar scan of the hand. Our evaluation targets: (1) rankings of individual fingers with respect to minutiae and eigenfinger features; (2) fusion of multi-instance intra-feature (minutiae or eigenfinger) matching scores; (3) cross-feature compared to intra-feature performance; (4) optimal weights for weighted versions of five score-level fusion methods – max, median, min, product and sum and (5) aspects of computational demands for hand-based identification discussing the usage of serial classifier combinations instead of classically employed parallel ones. We examine results of an experimental approach to the problem of finding a suitable fusion method by investigating the effect of matcher-specific combination weights on recognition accuracy and compare cross-feature and intra-feature score combinations.

Keywords: hand biometrics; score-level combination; multi-instance fusion; eigenfingers; fingerprint; serial classifiers.

Reference to this paper should be made as follows: Uhl, A. and Wild, P. (2009) 'Single-sensor multi-instance fingerprint and eigenfinger recognition using (weighted) score combination methods', *Int. J. Biometrics*, Vol. 1, No. 4, pp.442–462.

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Peter Wild is a PhD student at the Department of Computer Sciences, University of Salzburg, Austria, and a Lecturer at the Salzburg University of Applied Sciences, Austria. He received his Master's degree in applied computer science from the University of Salzburg, Austria. His research interests are related to pattern recognition, multibiometrics and multimedia security.


Enhancing Iris Matching Using Levenshtein Distance with Alignment Constraints

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COMPUTATIONALLY EFFICIENT SERIAL COMBINATION OF ROTATION-INVARIANT AND ROTATION COMPENSATING IRIS RECOGNITION ALGORITHMS

Mario Konrad, Herbert Stögner

Andreas Uhl, Peter Wild

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Incremental Iris Recognition: A Single-algorithm Serial Fusion Strategy to Optimize Time Complexity

Christian Rathgeb, Andreas Uhl and Peter Wild

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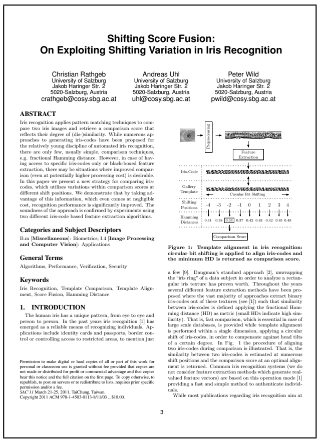
http://dx.doi.org/10.1109/BTAS.2010.5634475


Shifting Score Fusion:
On Exploiting Shifting Variation in Iris Recognition
Christian Rathgeb, Andreas Uhl, Peter Wild
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C. Rathgeb, A. Uhl, and P. Wild. Shifting Score Fusion: On Exploiting Shifting Variation in Iris Recognition. In *Proceedings of the 26th ACM Symposium on Applied Computing (SAC'11)*, pages 3–7, TaiChung, Taiwan, March 21–24, 2011.

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On Combining Selective Best Bits of Iris-Codes*
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C. Rathgeb, A. Uhl, and P. Wild. On Combining Selective Best Bits of Iris-Codes. In C. Vielhauer et al., editors, *Proceedings of the Biometrics and ID Management Workshop (BioID'11)*, volume 6583 of *LNCS*, pages 227–237, Brandenburg on the Havel, Germany, March 8–10, 2011.

http://dx.doi.org/10.1007/978-3-642-19530-3_21


Iris-Biometric Comparators: Minimizing Trade-Offs Costs between Computational Performance and Recognition Accuracy
Christian Rathgeb, Andreas Uhl and Peter Wild
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C. Rathgeb, A. Uhl, and P. Wild. Iris-Biometric Comparators: Minimizing Trade-Offs Costs between Computational Performance and Recognition Accuracy. In *Proceedings of the 4th International Conference on Imaging for Crime Detection and Prevention (ICDP'11)*, 6 pages, London, UK, November 3–4, 2011.

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Iris Recognition in Image Domain: Quality-Metric Based Comparators*

Heinz Hofbauer, Christian Rathgeb, Andreas Uhl, and Peter Wild

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Image Metric-based Biometric Comparators: A Supplement to Feature Vector-based Hamming Distance?

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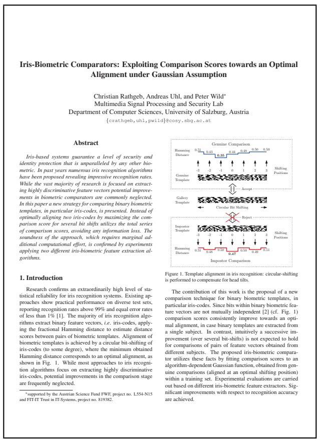

Iris-Biometric Comparators: Exploiting Comparison Scores towards an Optimal Alignment under Gaussian Assumption

Christian Rathgeb, Andreas Uhl, and Peter Wild

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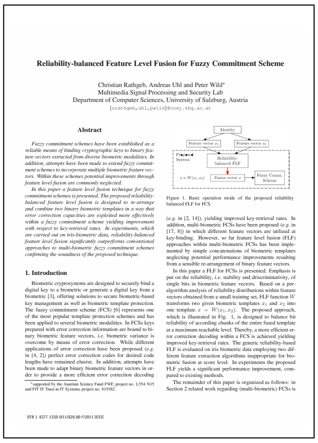
Reliability-balanced Feature Level Fusion for Fuzzy Commitment Scheme

Christian Rathgeb, Andreas Uhl and Peter Wild

C. Rathgeb, A. Uhl, and P. Wild. Reliability-balanced Feature Level Fusion for Fuzzy Commitment Scheme. In *Proceedings of the 1st International Joint Conference on Biometrics (IJCB'11)*, 7 pages, Washington, DC, USA, October 10–13, 2011.

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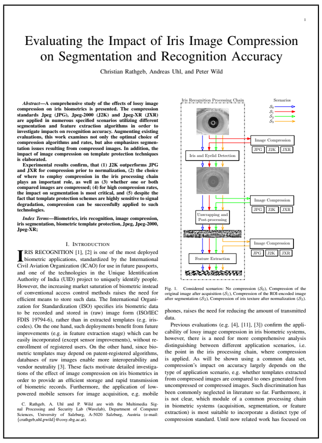
Evaluating the Impact of Iris Image Compression on Segmentation and Recognition Accuracy

Christian Rathgeb, Andreas Uhl, and Peter Wild

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3. Conclusion

Iris biometrics has been an active research field in recent years [6] and is considered a key biometric technology capable of large-scale deployment, see its current application in India's Aadhaar project [74]. While iris recognition technologies have been shown to work well in sufficiently constrained environments [79, 5], their application in surveillance scenarios is still a challenging task requiring the interplay of all modules in the iris biometric processing chain [60]: (1) *image acquisition* requires sufficiently high resolution to provide at least 100 pixels iris diameter (as required per ISO/IEC 19794-6 quality "low"), reliable auto-focus permitting large capture volumes (depth-of-field), and fair illumination without causing too many reflective spots in eye images precluding the extraction of texture information at the respective locations; (2) *image preprocessing* capabilities including reliable eye detection, iris segmentation and normalization techniques tolerating most of the variability (off-axis iris images, motion blur, defocus, VW versus NIR); (3) *feature extraction* being both fast and accurate for real-time extraction of stable properties usable for identification and; (4) *comparison*, which should ideally be even more tolerant with respect to segmentation inaccuracies and other quality degrading factors. This thesis has concentrated and presented contributions with respect to modules (2) and (4). The following sections discuss these contributions and remaining issues and challenges in more detail.

3.1. Author's Contribution

This section comprehensively discusses the key results of this thesis. The main contributions of this work with respect to iris segmentation are:

1. a survey of iris segmentation techniques [61], as well as an application-specific evaluation of the impact of compression on iris segmentation and accuracy [55];
2. a new multi-stage iris segmentation framework [72] based on a refined version of [8], with two reference implementations: WAHET [73] (Weighted Adaptive Hough and Ellipsopolar Transforms), and IFPP [72] (Iterative Fourier-based Pulling and Pushing);
3. a novel fast combination technique of face and face-part detectors [71] able to operate on NIR (tested on CASIA.v4-Distance) as well as VW data (tested on Yale-B database).

With respect to contribution (1) it turned out, that a variety of iris segmentation approaches exist, which typically follow Daugman's normalization model [14] and focus on either *preprocessing*, *boundary localization* or *postprocessing* techniques. Experiments [73, 72, 55] yielded a very critical role of the boundary localization sub-task with respect to segmentation errors. Approaches are analyzed in classes based on refinements of the Integro-differential operator [14], Hough transform [81], active contours [62, 1], model-fitting and polar techniques [61]. Only few techniques satisfactory fulfill all three quality criteria of segmentation (*accuracy, usability* and *speed* [61]). From the three considered compression scenarios (compression of the original image, ROI-compression after segmentation, and compression after normalization), a tradeoff between effectiveness (most effective for original images) and the impact on segmentation has been found (with compression standard JPEG-2000 delivering the best experimental results before JPEG and JPEG-XR). Claimed denoising capabilities of slight compression even assisting in the segmentation process as raised in [27, 17], have been confirmed.

Contribution (2) consists of two methods explicitly targeting all three quality criteria: WAHET is based on the sequential extraction of iris boundaries assisting the less pronounced boundary (typically limbic in case of NIR and pupillary in case of VW) by employing an ellipsopolar transform. Results comparing the proposed method with classical circular Hough transform and active contour based techniques highlighted the problem of database-specific optimizations [73]. This result confirms claims in [44] that heterogeneous NIR and VW processing is still not a completely solved problem (with many approaches employing not interdependent [60], but fixed-order boundary localization). The proposed method [73] outperformed the open source OSIRIS [34] tool on tested datasets (1.2% EER vs. 16.4% EER on Casia-I, 4.36% EER vs. 14.89% EER on Casia-L, 12.9% EER vs. 15.45% EER on ND) as well as contrast-adapted Hough transform based segmentation (except for Casia-I the method was tuned for) needing a fraction of processing time of classical techniques (0.21–0.26 seconds processing time per image vs. 3.46–6.27 seconds for OSIRIS), and will soon be available online (see [58]) as a donation to the scientific community. Also IFPP based on a repeated application of Fourier-based trigonometry and pulling and pushing methods showed more robustness against changes in the underlying recording conditions, albeit recognition rates were not as high as for WAHET.

By combining limited detection capabilities of individual detectors, contribution (3) is a technique taking spatial relationships of detection responses (i.e., prior knowledge) into account, which in contrast to cascaded techniques [77] is able to reduce also false negatives. Results with respect to detection rate (DR) illustrate, that not only a more robust detector is obtained (96.4 % DR versus 65.8% DR for the single detector and 14.6% DR for the nested detector on CASIA.v4-Distance, 99.2% DR versus 97.6% DR and 87.3% DR on Yale-B, respectively), but also processing time overhead for the exhaustive test is negligible in case detectors provide reasonable accuracy [71].

Main contributions with respect to biometric comparators as an alternative to the widely employed HD for comparison are:

4. the proposal of alignment-optimized comparators [70, 54, 56] exploiting even more information during the alignment process, thus yielding higher accuracy;

5. an investigation of serial comparison schemes [68, 33, 50] yielding several techniques speeding up the comparison in identification mode;

6. the introduction of a bit-reliability based multi-algorithm fuzzy commitment scheme [53] for enhanced privacy of biometric templates;

7. the application of comparators in the image domain [25, 24] as a means to increase recognition accuracy when combined with traditional techniques;

8. the combination (fusion) of proposed techniques to further enhance comparison [51].

By providing numerous new biometric comparators, ranging from simple improvements [54] requiring only few additional calculations to sophisticated techniques exploiting bit-reliability and early rejection [50], comparators can be chosen according to application-specific demands. Especially the constrained Levenshtein Distance (LD) comparator [70] delivered excellent comparison performance tolerating non-linear distortions on the challenging ICE dataset (4.96% EER versus 8.6% EER for standard HD-based comparison using Ma's feature extraction [38]), thus seems to be ideally suited for surveillance-type images. In case fast comparison (constrained LD needs 4-5 times more processing time) is required, e.g. for video-based identification, [54, 56] are comparators requiring only little modifications to existing HD-based comparators delivering higher accuracy, especially for high security applications with requested low false accepts (1.94% ZeroFMR vs. 4.87% ZeroFMR for HD using Ma in case of sifting score fusion [54], 95.56% GAR at 0.01% FAR vs. 91.74% GAR for HD using Masek in case of Gaussian score fitting combined with HD).

Evaluations related to contribution (5) have shown, that by learning global reliability masks, unseen iris-codes can be re-arranged concentrating more reliable bits at early positions (i.e. constituting an alternative to noise masks), and that an incremental computation of resorted iris-codes (according to bit-reliability) can save huge amounts of processing time at almost no degradations in performance (bit-comparisons can be reduced to less than 5% of comparisons at almost the same accuracy) [50]. Furthermore, results in [50] have shown, that a random permutation of bits can already increase partial matching accuracy (in case no training data for reliability masks is available). As an alternative approach for speeded-up identification [33] has proposed pre-screening using rotation-invariant features [18], which could save 70–80% of computational time in tested configuration at almost the same accuracy. This technique is based on considerations in [68] comparing parallel and serial approaches and investigating multi-biometric pre-screening techniques with the aim of getting higher accuracy without the drawback of increased comparison time.

Contribution (6) proposed a reliability-balanced feature level fusion technique for an FCS balancing the average reliability of the template, thus increasing the effectiveness (5.56% FRR versus 10.97% FRR at FAR < 0.01 for the ordered version) of the underlying error-correction code [53]. Again, random permutations were shown to be better than the original ordering of bits.

With respect to the application of image quality metrics in image domain in contribution (7) it has been shown, that contradicting to common belief that original images exhibit too much degrees of freedom to be used directly for iris recognition standard quality metrics are usable in the recognition process. Albeit not as accurate as classical feature-vector based techniques metrics tracking structural similarity (SSIM), local edge gradients (LEG), image contours (NICE) or even rather simple approaches like peak signal-to-noise ratio (PSNR) are useful, especially in case of processing normalized images, e.g., as predictors or additional classifiers to be combined with traditional techniques. The latter use is evaluated even more exhaustively in [24] identifying LFBVS+VIF (1.86% EER) as the best metric–metric combination and Ma+LEG (1.32% EER) as the best iris-code–metric combination (compared to 1.43% EER for Ma, 1.77% EER for Masek only).

Finally, contribution (8) refers to the application of fusion techniques to combine some of the proposed techniques, in particular the idea of user-specific reliable bits [49] and shifting score fusion [54], which turned out to further increase performance (97.77% GAR at 0.01% FAR versus 96.35% GAR for Masek).

While a direct comparison of comparators due to different focus (e.g., the constrained Levenshtein comparator unfolds its full potential not until sufficiently large maximum offsets are specified) is a difficult task, [59] lists further results for presented comparators employing a common experimental setup for comparators targeting similar scenarios.

3.2. Issues and Challenges

Summarizing this thesis, the author has contributed novel approaches with respect to two major factors in iris biometric surveillance: new advanced segmentation algorithms and biometric comparators. While these two modules are not the only relevant factors, segmentation has been shown to be one of the key problems to be solved for successful application of biometric methods in surveillance [44, 70, 73, 71, 72]. However, apart from the segmentation problem being critical for the automated online recognition task (e.g., verification for cash withdrawals at ATMs or online covert negative identification against a watch-list of suspects), there are also offline forensic applications (e.g., offline analysis of surveillance data for identification of suspects in case of fraud) requiring the exploit of every bit of information present in the underlying data. For the latter case enhanced biometric comparators trying to tolerate segmentation errors, enhancing comparison speed and increasing accuracy seem to be a rather good method to target challenges in the field.

Apart from the issues targeted in this thesis, of course iris biometric surveillance raises a few other questions to be addressed, e.g., the optimization of image capture conditions and selection of hardware solving the problems of quick focal assessment and illumination of the scenery without violating the covert acquisition constraints. New techniques like digital light field photography [41] permitting a post-capture solution of the focus problem in photography, or the constantly growing resolution of cameras dropping in price are opening new possibilities, which can and should be exploited for iris-biometric surveillance in the future. Finally, also enforced standardization, like the standard on "Biometric Data Interchange Formats" (ISO/IEC FDIS 19794-6) or ongoing "Biometric Sample Quality Standard" (ISO/IEC CD 29794-6), alleviate modularized systems with exchangeable modules. Also long-term iris stability is an active research topic [4, 3], which should be addressed in the realm of biometric evidence for forensic investigation from surveillance data. Finally, the interplay of face, iris and periocular biometrics is being studied by researchers [78, 31], which may lead to even more tightly coupled integrated systems in the future. With the recent rise of periocular biometrics a merger of face and iris biometrics techniques is to be expected, which also constituted the realm of the project BioSurveillance "Single-sensor biometric surveillance combining iris and face", this dissertation originated from.

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A. Appendix

A.1. Breakdown of Authors' Contribution

This section lists a breakdown of authors' contribution with respect to the publications included in this thesis. All author names appear in alphabetical order on the publications.

Andreas Uhl is/was the thesis advisor/project leader of Heinz Hofbauer, Mario Konrad, Christian Rathgeb and Peter Wild. Mario Konrad has also been supervised by Herbert Stögner. Since the explicit contribution of an advisor and project leader cannot be stated for a single paper, it is omitted in the following breakdown.

	Contribution (in %)					
Publication	Heinz Hofbauer	Mario Konrad	Christian Rathgeb	Herbert Stögner	Andreas Uhl	Peter Wild
C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 1 (The Human Iris as a Biometric Identifier), pages 3–6. Advances in Information Security. Springer, New York, 2012. To appear			50			50
C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 2 (Iris Biometric Processing), pages 7–19. Advances in Information Security. Springer, New York, 2012. To appear			20			80
C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 3 (State-of-the-Art in Iris Biometrics), pages 21–36. Advances in Information Security. Springer, New York, 2012. To appear			10			90

Publication	Heinz Hofbauer	Mario Konrad	Christian Rathgeb	Herbert Stögner	Andreas Uhl	Peter Wild
	Contribution (in %)					
C. Rathgeb, A. Uhl, and P. Wild. *Iris Recognition: From Segmentation to Template Security*, chapter 5 (Iris Segmentation Methodologies), pages 49–72. Advances in Information Security. Springer, New York, 2012. To appear						100
A. Uhl and P. Wild. Combining Face with Face-Part Detectors under Gaussian Assumption. In A. Campilho and M. Kamel, editors, *Proceedings of the 9th International Conference on Image Analysis and Recognition (ICIAR'12)*, volume 7325 of *LNCS*, pages 80–89, Aveiro, Portugal, June 25–27, 2012. Springer. doi: 10.1007/978-3-642-31298-4_10						100
A. Uhl and P. Wild. Weighted Adaptive Hough and Ellipsopolar Transforms for Real-time Iris Segmentation. In *Proceedings of the 5th International Conference on Biometrics (ICB'12)*, 8 pages, New Delhi, India, March 29–April 1, 2012. IEEE						100
A. Uhl and P. Wild. Multi-stage Visible Wavelength and Near Infrared Iris Segmentation Framework. In A. Campilho and M. Kamel, editors, *Proceedings of the 9th International Conference on Image Analysis and Recognition (ICIAR'12)*, volume 7325 of *LNCS*, pages 1–10, Aveiro, Portugal, June 25–27, 2012. Springer. doi: 10.1007/978-3-642-31298-4_1						100
A. Uhl and P. Wild. Parallel versus Serial Classifier Combination for Multibiometric Hand-Based Identification. In M. Tistarelli and M. Nixon, editors, *Proceedings of the 3rd International Conference on Biometrics (ICB'09)*, volume 5558 of *LNCS*, pages 950–959, Alghero, Italy, June 2–5, 2009. Springer. doi: 10.1007/978-3-642-01793-3_96						100
A. Uhl and P. Wild. Single-sensor multi-instance fingerprint and eigenfinger recognition using (weighted) score combination methods. *International Journal on Biometrics*, 1(4):442–462, 2009. Inderscience. doi: 10.1504/IJBM.2009.027305						100

Publication	Contribution (in %) Heinz Hofbauer	Mario Konrad	Christian Rathgeb	Herbert Stögner	Andreas Uhl	Peter Wild
A. Uhl and P. Wild. Enhancing Iris Matching Using Levenshtein Distance with Alignment Constraints. In G. Bebis et al., editors, *Proceedings of the 6th International Symposium on Advances in Visual Computing (ISVC'10)*, volume 6453 of *LNCS*, pages 469–479, Las Vegas, NV, USA, November 29–December 1, 2010. Springer. doi: 10.1007/978-3-642-17289-2_45						100
M. Konrad, H. Stögner, A. Uhl, and P. Wild. Computationally efficient serial combination of rotation-invariant and rotation compensating iris recognition algorithms. In *Proceedings of the 5th International Conference on Computer Vision Theory and Applications (VISAPP'10)*, volume 1, pages 85–90, Angers, France, May 17–21, 2010. SciTePress		80				20
C. Rathgeb, A. Uhl, and P. Wild. Incremental Iris Recognition: A Single-algorithm Serial Fusion Strategy to Optimize Time Complexity. In *Proceedings of the IEEE 4th International Conference on Biometrics: Theory, Applications, and Systems (BTAS'10)*, 6 pages, Washington, DC, USA, September 27–29, 2010. IEEE. doi: 10.1109/BTAS.2010.5634475			50			50
C. Rathgeb, A. Uhl, and P. Wild. Shifting Score Fusion: On Exploiting Shifting Variation in Iris Recognition. In *Proceedings of the 26th ACM Symposium On Applied Computing (SAC'11)*, pages 3–7, TaiChung, Taiwan, March 21–24, 2011. ACM. doi: 10.1145/1982185.1982187			50			50
C. Rathgeb, A. Uhl, and P. Wild. On Combining Selective Best Bits of Iris-Codes. In C. Vielhauer et al., editors, *Proceedings of the Biometrics and ID Management Workshop (BioID'11)*, volume 6583 of *LNCS*, pages 227–237, Brandenburg on the Havel, Germany, March 8–10, 2011. Springer. doi: 10.1007/978-3-642-19530-3_21			30			70

Publication	Contribution (in %)					
	Heinz Hofbauer	Mario Konrad	Christian Rathgeb	Herbert Stögner	Andreas Uhl	Peter Wild
C. Rathgeb, A. Uhl, and P. Wild. Iris-Biometric Comparators: Minimizing Trade-Offs Costs between Computational Performance and Recognition Accuracy. In *Proceedings of the 4th International Conference on Imaging for Crime Detection and Prevention (ICDP'11)*, 6 pages, London, UK, November 3–4, 2011. IET. doi: 10.1049/ic.2011.0110			50			50
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