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Kevin W. Bowyer · Mark J. Burge  
Editors

# Handbook of Iris Recognition

Second Edition

 Springer

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*Divine Iris, what god sent you to me with a message?*

—Homer, *Iliad*

*Let every eye negotiate for itself and trust no agent.*

—William Shakespeare,  
*Much Ado About Nothing*

# Foreword

Four years after the publication of the first edition of the Handbook of Iris Recognition, we are pleased to present this updated and reorganized edition featuring four new and four revised chapters. We hope that you will enjoy the new edition.

Kevin W. Bowyer and Mark J. Burge, January 2016

The arrival of this Handbook in 2012 suitably marks a number of milestones and anniversaries for iris recognition. The most breathtaking of these is the fact that now on a daily basis more than 100 trillion, or 10-to-the-14th-power, iris comparisons are performed. This juggernaut (a Hindi word, appropriately) was unleashed by the Indian Government to check for duplicate identities as the Universal Identification Authority of India, or UIDAI, enrolls the iris patterns of all its 1.2 billion citizens within 3 years. This vastly ambitious program requires enrolling about 1 million persons everyday, across 36,000 stations operated by 83 agencies. Its purpose is to issue each citizen a biometrically provable unique entitlement number (Aadhaar) by which benefits may be claimed, and social inclusion enhanced; thus the slogan of UIDAI is: “To give the poor an identity.” With about 200 million persons enrolled so far, against whom the daily intake of another million must be compared for de-duplication, the daily number of iris cross-comparisons is about 10-to-the-14th-power, and growing. Similar national projects are also underway in Indonesia and in several smaller countries.

Also breathtaking (but perhaps mainly just for me personally) is the fact that this year is only the 20-year anniversary of the first academic paper proposing an actual method for iris recognition. In August 1992, having recently arrived at Cambridge University as a Research Fellow, I submitted a paper about the method to *IEEE Transactions on Pattern Analysis and Machine Intelligence* (PAMI) entitled: “High confidence visual recognition of persons by a test of statistical independence.” The core theoretical idea was that the *failure* of a test of independence could be a very strong basis for pattern recognition, if there is sufficiently high entropy (enough degrees-of-freedom of random variation) among samples from different classes, as I was able to demonstrate with a set of 592 iris images. The PAMI paper was published in 1993, shortly before my corresponding US

Patent 5,291,560 was also issued. That original algorithm was widely licensed through a series of companies (IriScan, Iridian, Sarnoff, Sensor, LG-Iris, Panasonic, Oki, BI2, IrisGuard, Unisys, Sagem, Enschede, Securimetrics, and L1 now owned by Safran/Morpho). With various improvements over the years, this algorithm remains today the basis of all significant public deployments of iris recognition. But academic research on many aspects of this technology has exploded in recent years. To quote from the excellent survey chapter by Bowyer, Hollingsworth, and Flynn in this book: during just the 3-year period, 2008–2010, there were more papers published about iris recognition than during the entire 15-year period, 1992–2007.

The conjecture that perhaps the iris could serve as a fingerprint has a much longer history, and this year marks the 60-year anniversary of the following statement in Adler's classic clinical textbook *Physiology of the Eye* (Chap. 6, page 143): "In fact, the markings of the iris are so distinctive that it has been proposed to use photographs as a means of identification, instead of fingerprints." Apparently, Adler referred to a proposal by the British ophthalmologist Duggart. In the 1980s, two American ophthalmologists, Flom and Safir managed to patent Adler's and Duggart's conjecture, but they had no actual algorithm or implementation to perform it and so the patent was conjecture. The roots of the conjecture stretch back even further: In 1892, Alphonse Bertillon documented nuances in "Tableau de l'iris humain"; and divination of all sorts of things based on iris patterns goes back to ancient Egypt, Babylonia, and Greece. Iris divination persists today, as "iridology."

Optical systems for iris image acquisition have enjoyed impressive engineering advances, enabling generally a more flexible user interface and a more comfortable distance between camera and subject than the "in-your-face" experience and the "stop-and-stare" interface of the first cameras. Pioneering work by Jim Matey and his team at Sarnoff Labs led to the current generation of systems capturing "iris-at-a-distance" and "iris-on-the-move," in which capture volume is nearly a cubic meter and on-the-move means walking at 1 m/s, enabling throughput rates of a person per second. There has been a "long-distance race" to demonstrate the longest standoff distance, with some claims extending to the tens of meters. The camera is then essentially a telescope, but the need to project enough radiant light safely onto the target to overcome its inverse square law dilution is a limitation. These developments bring two wry thoughts to my mind: First, I recall that when I originally began giving live demonstrations of iris recognition, the capture volume was perhaps a cubic inch; the hardware was a wooden box containing a video camera, a video display, a near-infrared light source, and a voice interface that replayed the name of a person when visually identified. Second, I read that the Hubble Space Telescope is to be decommissioned, and I wonder whether we might convert it into the Hubble Iris Camera for the ultimate "iris-at-a-distance" demonstration....

In the first dozen years after the 1993 PAMI paper, it was always very difficult to persuade leaders of the established biometrics community to take an interest in the claim that the iris algorithm had extraordinary resistance against False Matches, as well as enormous matching speed. The encoding of an iris pattern into a sign bit sequence enables not only extremely fast XOR matching (e.g., on a 32-bit machine,

32 parallel bits from each of two IrisCodes can be simultaneously compared in a single machine instruction, in almost a single clock cycle at say 3 GHz). But even more importantly, the Bernoulli nature of random bit pair comparisons generates binomial distributions for the (dis)similarity scores between different eyes. The binomial distribution (for “imposter” comparisons) is dominated by combinatorial terms with geometric tails that attenuate extremely rapidly. For example, if you accept as a match any IrisCode pair for which no more than 32 % of the bits disagree, then the False Match likelihood is about 1 in a million; but if your criterion is just slightly stricter, say that no more than 28 % of the bits may disagree, then the False Match likelihood is about 1 in a billion (i.e., reduced by a further thousand-fold as result of a mere 4-percentile point [0.04] reduction in threshold). These claims became contentious in the year 2000 when the Director of the US “National Biometric Test Center” (NBTC) in San Jose wrote that in their testing of an iris recognition prototype at NBTC, many False Matches have been observed. I received copies of all the images, ran all-against-all cross-comparisons, and sure enough, there were many apparent False Matches. But when I inspected these putative False Match images visually, it became clear that they were all in fact True Matches but with changed identities. The Director of the NBTC later confirmed this and generously acknowledged: “Clearly we were getting scammed by some of our student volunteers (at \$25 a head, they were changing names and coming through multiple times).”

Another obstacle to confirmation of the extreme resistance of this biometric to False Matches was the decision in the first large-scale test (ICE 2006: *Iris Challenge Evaluation*) to evaluate at a False Match Rate of 1 in a thousand ( $FMR = 0.001$ ). In this very nondemanding region of an ROC plot, most biometrics will appear equally powerful. Indeed, since ROC curves converge into the corners at either extreme, if one tested at say  $FMR = 0.01$ , then probably the length of one’s big toe would seem as discriminating as the iris. The long tradition of face recognition tests had typically used the  $FMR = 0.001$  benchmark for obvious reasons: face recognition cannot perform at more demanding FMR levels. Thus the ICE 2006 Report drew the extraordinary conclusion that face and iris were equally powerful biometrics. Imagine how well face recognition would hold up in the 100 trillion daily cross-comparisons done by UIDAI. And if iris were operating at the  $FMR = 0.001$  level, then everyday in UIDAI there would be 100 billion False Matches—a number equal to the number of stars in our galaxy, or of neurons in the human brain.

A critical feature of iris recognition is that it produces very flat ROC or DET curves. By threshold adjustment, the FMR can be shifted over four or five orders of magnitude while the FnMR hardly changes. Thus at  $FMR = 0.001$  iris may appear unremarkable, as in ICE 2006, and so Newton and Phillips (2007) disputed “the conventional wisdom” that iris was a very powerful biometric. But hardly any price is paid in iris FnMR when its FMR is shifted by several log units, to 0.0000001 or smaller, as required for national-scale deployments. Fortunately, tests by NIST subsequent to ICE have understood this point about the likelihood ratio (the slope of the ROC curve) and have pushed iris testing into the billions of

cross-comparisons (IREX-I) and indeed now 1,200 billion cross-comparisons (IREX-III). IREX-I confirmed (7.3.2) that “there is little variation in FnMR across the five decades of FMR,” and also confirmed exactly the exponential decline in FMR with minuscule (percentile point) reductions in threshold as I had tabulated in earlier papers. IREX-III results (presented by Patrick Grother in London, October 2011) included a comparison of iris and face performance using the best face algorithms from 2010 on a database of 1.6 million mugshot face images (compliant with a police mugshot standard), and also 1.6 million DoD detainee iris images. These NIST tests showed that for any plausible FnMR target, iris recognition makes 100,000 times fewer False Matches than face.

I am delighted to see the range of topics included in this Handbook, which reflects in part the richness of our subject and all the connections it draws among biology, photonics, optical engineering, security engineering, mathematics, algorithms, and standardization. Especially, hot current topics include iris image quality metrics, with the recent NIST report (IREX-II or IQCE) on quality-performance covariates and their predictive powers across matchers, and current development of an ISO/IEC Standard (29794-6) for quality. One area that remains rather unexplored is the role of information theory, which lies at the heart of our subject since it measures both the complexity of random variation (the key to biometric collision avoidance), and discriminating power.

Twenty years is a remarkably short time to get from 0 to 100 trillion iris comparisons per day. But also, 20 years is perhaps a generation. It feels as though the real potential of this technology is just beginning to be understood (as can probably also be said about its limitations). This Handbook—the first book to be devoted entirely to iris recognition—is full of excellent contributions from a new generation of researchers. If I have been a torchbearer, I am all too happy to “pass the torch” to them while remaining, I hope, still on the field amidst increasing numbers of colleagues captivated by the entropy of the eye.

Cambridge  
February 2012

John Daugman

## Preface to the Second Edition

Creating the Second Edition of the Handbook of Iris Recognition is somehow more challenging and ambitious than creating the first edition. This is because iris recognition continues to develop simultaneously in both practical applications and fundamental research. On the practical application side, iris recognition is increasingly used with success in demanding, large-scale applications. Perhaps, the most prominent example of this is the Aadhaar program administered by the Unique ID Authority of India. Over one billion persons have already been enrolled in the Aadhaar program. This is over three times the population size of the United States! The Aadhaar program registers people with both fingerprint and iris. A report from the Center for Global Development compared fingerprint and iris recognition results from the program and stated—“UID’s data suggest that iris scans are far more inclusive than fingerprints ... They are also more precise for authentication, in terms of having a lower tradeoff curve between errors of acceptance and rejection.” This sort of comparison statement would once have been highly controversial, but now seems broadly accepted. Another long-running application of iris recognition is the United Arab Emirates’ border-crossing application that has been in place for well over a decade. And a more recent application is the use of iris recognition to create a duplicate-free voter registration list for new elections in Somaliland.

On the research side, many fundamental and fascinating questions are being addressed in the research community. Advances on these topics hold the promise of improving future applications of iris recognition. A number of current topics in the iris recognition research community have the aim of improving the use of iris recognition at high accuracy for whole populations. Examples of this can be seen in new chapters added to the Second Edition, authored by Czajka, by Nigam, Vatsa and Singh, and by Bolme and coworkers.

The new chapter by Czajka explores the issue of “liveness testing” for iris recognition, based on the dynamic nature of the pupil. The new chapter by Nigam, Vatsa, and Singh explores and catalogs various eye conditions that will be encountered in serving whole populations, and discusses the effects of these

conditions on iris recognition. The new chapter by Bolme and coworkers looks in depth at the issue of correcting for images where the iris is seen in an off-angle view. The new chapter by Rathgeb and coworkers gives a system-level view of the flow of processing in an iris recognition system, along with an introduction to the open-source implementation provided by their lab. The revised chapter by Proença updates the corresponding chapter that appeared in the first edition. Proença is research community's best-known advocate in the for performing iris recognition using visible-light images rather than near-infrared images, and exploiting the use of visible-light imaging to allow less-constrained image acquisition.

The new iris segmentation chapter by Jillela and Ross also updates a corresponding chapter in the first edition. In many ways, the potential for improvement in iris recognition accuracy seems to be greater through improvements in segmentation than through improvements in coding or matching. This chapter gives an appreciation of the difficulty of the problem as well as of the current state of the art. The new chapter by Galbally and coworkers replaces the corresponding chapter in the first edition. This chapter is an excellent example of the collaborative spirit in the iris recognition research community. The two major research groups in the area of iris image reconstruction from iris codes have teamed up to provide an introduction to the state of the art on this topic.

## **Organization and Features**

As already mentioned above, there are four new chapters added to the Second Edition of the Handbook of Iris Recognition. This results in over 100 pages of new material. In addition, four other chapters have undergone major revision and updating, resulting in another 100 pages of revised material. The result is a combination of broader coverage of topics than in the first edition, as well as deeper coverage of selected topics.

This Second Edition of the Handbook of Iris Recognition includes a Foreword by the Father of Iris Recognition, Professor John Daugman, along with 23 contributed chapters. The 59 contributing authors come from a wide range of different companies, government agencies, and universities. They also come from many different countries, including Austria, Canada, Denmark, Germany, Hong Kong, India, Lithuania, Poland, Portugal, Singapore, the United Kingdom, and the USA.

## **Target Audiences**

There are multiple target audiences for the Handbook of Iris Recognition, brought together by the theme of needing a better understanding of the current state of the art in this field. Anyone new to the field of iris recognition and needing to quickly get a big-picture view of the field should find the Handbook quite useful.

Any potential consumer of iris recognition technology wanting a sober appraisal of the current state of the art should find it here. Any researcher looking for ideas of where and how to usefully advance the state of the art in iris recognition should find a wealth of ideas here.

## Acknowledgments

Special thanks are due to authors of chapters in the first edition who took on the task of revising and updating their chapter: Hugo Proença for the chapter on visible-light iris recognition, Raghavender Jillela and Arun Ross for the chapter on methods for iris segmentation, and Javier Galbally, Marios Savvides, Shreyas Venugopalan, and Arun Ross for the chapter on iris image reconstruction from binary templates. Special thanks are due as well to the authors of new chapters: Adam Czajka for the chapter on iris liveness detection, Ishan Nigam, Mayank Vatsa, and Richa Singh for the chapter on the menagerie of ophthalmic disorders that affect iris recognition, Christian Rathgeb, Andreas Uhl, Peter Wild, and Heinz Hofbauer for the chapter on design decisions for an iris recognition SDK, and David S. Bolme, Hector Santos-Villalobos, Joseph Thompson, Mahmut Karakaya, and Chris Bensing Boehnen for the chapter on methods of correcting off-angle iris images. All of these authors have done an excellent job of improving the coverage and quality of the Handbook.

We again thank our editors at Springer for their patience and encouragement. We again would like to thank our families for their support over the evening and weekend time needed to make the Handbook a reality.

Notre Dame, IN, USA  
Washington, DC, USA  
January 2016

Kevin W. Bowyer  
Mark J. Burge

# **Preface to the First Edition**

Iris Recognition became a practical area of technology and study with John Daugman's pioneering work about two decades ago. The development of the field was at first slow, but has expanded dramatically in recent years. There are now various national identity schemes in progress that make use of Iris Recognition technology. There is also a large and vibrant research community focused on Iris Recognition, studying ways to make it even more accurate in even larger scale applications. The primary goal of this book is to give an authoritative introduction to the current state of the art in Iris Recognition technology. The field has already, in large part, moved past the study of alternative segmentation algorithms and texture filters applied to pristine iris images. One major current emphasis is how to deal with varying quality iris images acquired with less-explicit user cooperation. Another major current emphasis is on methods for improving accuracy in the context of varying quality images. Still another major current emphasis is on a better understanding of the basic science underlying iris recognition. Each of these emphases is represented by multiple chapters in this book.

## **Organization and Features**

This book includes a Foreword by Professor John Daugman, along with a collection of 17 chapters contributed by researchers from around the world. It includes theoretical studies, such as the chapter by Clark, Culp, Herron and Ross on Iris Dynamics and the chapter by Kong, Zhang and Kamel on the Iris Code. It also includes very empirical studies, such as the chapter by Baker, Bowyer, Flynn, and Phillips on Iris Template Aging and the chapter by Phillips and Flynn analyzing results from the Iris Challenge Evaluation 2006. The 44 authors contributing to the book come from companies, government agencies, and universities. They also come from many different countries, including Lithuania, Canada, Singapore, Denmark, Portugal, Hong Kong, the United Kingdom, and the USA.

## **Target Audiences**

The target audience for this book is anyone who wants a better understanding of the current state of the art in Iris Recognition. Practitioners in industry should find new insights and possibilities in the breadth of topics covered. Managers and executives in government should find a more sober appraisal of the field than that exists in the marketing literature of the industry. Researchers in government, industry, and academia should find new ideas for productive research efforts.

## **Acknowledgements**

We would like to thank the editors at Springer for their patience and advice during the development of this project. We also would like to thank all of the contributors to this book for their prompt replies on various points. We would like to thank all of our collaborators at our respective institutions for the vibrant research atmosphere that they have provided. Finally, we would like to thank our families, for without their continual support and encouragement this book would not have been possible.

Notre Dame, IN, USA  
Washington, DC, USA  
January 2013

Kevin W. Bowyer  
Mark J. Burge

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