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PhD THESIS

Signal Processing Methodologies

– SUMMARY –

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Autoevaluation

The main objective of our thesis (*Signal Processing Methodologies*) is the study of digital signal processing methods with applications in *Iris Recognition*. The practical examples considered most often throughout the thesis come from this field, whereas the signals that we are working with are those encoded in the iris texture of the human eye, or signals derived therefrom.

Consequently, the digital signal processing methods discussed in this thesis cover the needs of this practical example, all of them belonging in either one of the following fields: *computer vision* (eye image segmentation, i.e. pupil and iris detection), *feature extraction and encoding* (binary encoding of the iris texture and of the digital identities, or custom encoding of the digital identities), *feature matching* (iris matching), *artificial intelligence* and *data understanding* (programming intelligent agents used to discover new processing methods or to improve existing ones; computer aided design for large scale intelligent biometric systems) and *formal modeling* for biometric systems (formal theories of signal similarity detection). In the later direction, we succeeded to formalize non-paradoxical self-referentiality in binary logic, *Consistent Biometry*, and *Turing-Zadeh paradigm* of intelligent recognition, all of them used to design the newly proposed paradigm of *Intelligent Iris Verifier* systems.

Regarding the iris segmentation, encoding and matching, we succedeed to give our own original solutions and to prove that the iris recognition results obtained by using them are at least comparable with the best iris recognition results documented in IREX 1 report. On the other hand, it is exemplified in this thesis that the use of recently proposed *Intelligent Iris Verifier* systems (which are evolutionary systems endowed with strong logical formal support) allowed us to give the best iris recognition results obtained and announced so far for the test database (Bath Database) and much more important, allowed us to advance from *statistical biometric safety* toward *absolute* (*logical*) *biometric safety*, from *fuzzy bimodal biometric decision* to *crisp binary biometric decision*.

In terms of experimental work, this thesis is supported by over 10,000 exhaustive iris recognition tests (each counting between 500,000 and 60,000,000 one-to-one comparisons), all of them performed on the public dataset *University of Bath Iris Image Database* and resulting in original conclusions and new results, some of them being published already [44] - [58], others following to be published soon (Chapter 5.1 - *Turing-Zadeh paradigm* of intelligent recognition / classification, for example).

Motivation

The topic explored in this thesis has two facets: one practical, with immediate applicability in the current technology of iris recognition, and one theoretical (yet), regarding the deep understanding of iris recognition as a subject of Artificial Intelligence, as a problem of encoding a concept (the digital identity) from known hypostases (binary iris codes). The stake in the second case is to achieve a logically coherent computational modeling of an intelligent agent endowed with suitable means that should enable it to prove an artificial understanding of similarity between the signals encoded within the iris texture - in particular, or similarity between other species of data – in general.

Choosing iris recognition as the main research subject of this thesis came from our belief (now confirmed by new results) that this branch of signal processing is still a pioneering area that provides the passionate researcher with a variety of unexplored paths, topics and views. We build this thesis toward these unexplored areas by searching for questions and answers (not necessarily in equal numbers) enabled to change the horizons of iris recognition (and those of the related domains) to the new coordinates of *logically consistent and intelligent iris recognition*.

From now on, starting with this thesis, the classical paradigm of statistical iris recognition finally has a better alternative, namely that of iris recognition practiced on evolutionary intelligent biometric systems (*Intelligent Iris Verifier*) in which the new biometric-decisional model is no longer bimodal (statistical), being a binary one instead, being one with absolute safety rates, one strongly cointensive with the reality of iris recognition objectively recorded by interrogating a human agent during a Turing test of iris recognition.

A Turing test shows that the recognition decisions given by a human agent are binary, crisp and correct (unconfused), whereas those usually given by a software agent (at the current state of the art stage) are bimodal, fuzzy and statistically confused. In other words, there is not enough *cointension* between the *human-oriented precisiation* and the *machine-oriented precisiation* of iris recognition, the *m-precisiation* (the meaning) of recognition practiced on artificial agents is not that of a human agent. Moreover, each of them is supposed to represent well (with cointension) the same event, namely the iris recognition. In short, this is the major contradiction within the current horizon of iris recognition and the main issue that this thesis aims to treat.

Outline

The complexity of the issues addressed in the thesis gradually increases to its final part, in tandem with the quality of the recognition results. In this thesis, the point at which the investigation of iris recognition begins, and also the point where all recognition results return for validation, is quite unexpected: the Turing test [71]. It is a relatively simple routine, which as will be noted throughout the thesis, has the power to bring a welcomed change of perspective in iris recognition: from a statistical theory of similarity, to a theory of intelligent recognition based on new and original soft computing models (Turing-Zadeh models for iris recognition) in which the concept of *cointensivity* plays the central role.

The research begins in **Chapter 2**, which illustrates the current state of research in the field of iris recognition. Chapter 2 contains a description of the pioneering phase of iris recognition (Flom, Safir, Daugman, Wildes), followed by a description of the current performance standard (*the state of the art*) in iris recognition as it is illustrated in the latest independent (and public) evaluation of iris recognition undertaken in 2007 by N.I.S.T. (National Institute for Standards and Technologies, USA) and recorded in the so called IREX 1 Report, [22]. On this occasion we show that the *test dataset* (University of Bath Iris Image Database, [72]) and the *test methodology* (*exhaustive iris recognition tests* based on *all-to-all comparisons*) adopted in the thesis is relevant for estimating the performance of iris recognition on *standard images* (as defined in IREX 1 Report, [22]).

Chapter 3 presents new *segmentation methods* (*RLE-FKMQ Based Pupil Finder*, *Circular Fuzzy Iris Segmentation*) and a new *encoding method* (*Hilbert Encoder*), techniques that we called *primary techniques* because they are obtained with no artificial intelligence support and they fits into a new but still *classical* approach to iris recognition in which the *biometric decision is still bimodal*, or in other words, they are new means for designing new iris recognition system but without exceeding the classical paradigm of *statistical iris recognition*. However, as it is outlined almost throughout the entire thesis (but especially in Chapter 4.2, Chapter 5 and Chapter 6), the bimodal biometric decision assumed in the theory of statistical iris recognition (initially proposed by Daugman [13], [16]) is not very much cointensive (or better saying, is not cointensive in values nor in meaning) with the *realistic biometric decision model* illustrated by recording the recognition decisions given by a human agent during a Turing test.

The primary techniques presented along the third chapter (*RLE-FKMQ Based Pupil Finder*, *Circular Iris Fuzzy Segmentation* and *Hilbert Encoder* or *Gabor Analytic Iris Texture Binary Encoder*) allowed us to obtain relatively quickly iris recognition results which are (at least) comparable with the results recorded in the report 'IREX 1 for *state of the art* recognition algorithms proposed by *Cambridge University*, *Cogent Systems*, *Crossmatch Technologies*, *Honeywell*, *Iritech*, *L*1 *Identity Solutions*, *LG*, *Neuro-technology*, *Reticle Systems* and *Sagem*. Thousands of exhaustive iris recognition tests undertaken while perfecting the techniques described in Chapter 3 gave us a correct understanding of the current horizons in iris recognition and this happened mainly because our tests were organized as Turing tests and because we always compared the automatic biometric decisions given by a simulated iris recognition system (an artificial agent) to those given by a human agent. By doing this way we accumulated a critical level of practical experience which further allowed us to formalize the Turing test as meta-theories of iris recognition (see the *Extended Turing-Zadeh Formal Model associated to an iris recognition Turing test* in Section 5.1.10) in which any given possible iris recognition theory (any iris recognition system explicitly known as a set of computation rules) can be compared to a realistic model of iris recognition which is implicitly known through examples of biometric decisions given by the human agent and formalized as a set of *cognitive implications* (Section 4.1).

An essential element found while doing Turing tests of iris recognition is that the statistical theory of iris recognition guarantees non-empty support for the *Liar Paradox*, (there are genuine/imposter pairs of iris codes which tell about themselves that *aren't* genuine/imposter pairs) whereas in the recorded practice of the human agent this does not happen at all: all pairs are recognized correctly as being *imposter* or *genuine* pairs without any kind of intermediary nuances between these two concepts. Clarifying the logical inconsistency situation revealed by the appearance of the *Liar Paradox* in the internal logic of a biometric system was made possible by creating a new formalization of binary logic - *Computational Cognitive Binary* (CCBL, introduced in **Chapter 4**) which hosts the *Cognitive Dialect* as a form of non-contradictory, well-formed and native self-referential logical discourse written *with* and *about* the propositional variables of (Classical) *Propositional Logic*. The principle of objectivity is set out here and provides necessary support for the computational substantiation of self-consciousness (self-awareness), for logically formalized artificial intelligent agents in general, and for smart biometric systems in particular. Chapter 4 then continues with the study of two fuzzy

logics that can describe the operation of a biometric system: a 2-valent inconsistent (confused) fuzzy logic induced by EER criterion, and an 8-valent fuzzy logic that hosts a *3-Valent Disambiguated Fuzzy Model* of iris recognition. To clarify logical aspects related to biometric verification and biometric identification, Section 4.3 outlines that in Consistent Biometry they are logically equivalent. The *Principle of Consistent Biometry* and the *Fundamental Theorem of Consistent Biometry* illustrate that verification and identification both carry the same semantic charge, namely the recognition of an individual.

Chapter 5 presents iris recognition as a topic of *Artificial Intelligence* and *Soft Computing*. The *Turing-Zadeh Formal Models* (TZM) of iris recognition are defined and proposed here. The relations between two such models are further expressed as a *Qualitative Sugeno Model* written in *Cognitive Dialect*. A TZM formally describing an iris recognition biometric system is a point in the formal meta-theory of iris recognition, is *a possible theory of iris recognition* more or less *cointensive* with the reality. An AFKD (Automatic Formal Knowledge Discovery) problem is further defined as being the problem of identifying through an informed search a new theory (of iris recognition, in this case) somewhere inbetween a perfectible TZM of iris recognition *precisiated* by a software agent (the start point of the search) and a precise (realistic) TZM of iris recognition *precisiated* by a human agent (the depiction of an ideal iris recognition theory known by examples). The c*ompatibility principle*, the *principle of efficient computational Turing-Zadeh modeling* and the *principle of reasonable speed-precision negotiation* are further formulated in order to avoid the possibility of building computationally *intractable TZMs of iris recognition* and/or *inconsistent formal theories of iris recognition*.

Chapter 6 is dedicated to a new paradigm of approaches to signal processing and iris recognition. Neural or neuro-evolutionary methods are used here in order to optimize existing primary techniques, to encode digital identities and to learn a formal theory of iris recognition. Efficient processing methods of signals derived from the iris image are identified as solutions to search/optimization problems addressed by applying AFKD techniques. Examples of this kind are: the optimized segmentation procedure (CFIS2 – the second version of *Circular Fuzzy Iris Segmentation*), the optimized binary encoders of the iris texture (*Wavelet-Hilbert*, *Multiscale Hilbert*, *Haar - Multiscale Hilbert*, the combined encoder *Log-Gabor & Haar - Multiscale Hilbert*) and the procedures for encoding stationary or evolutionary neural memories (discriminant directions or, more

generally, digital identities) needed for *Intelligent Iris Verifier* systems. Chapter 6 covers all of these topics.

The complex formal apparatus described in the thesis is a suitable context for identifying new iris recognition theories that are strongly cointensive with the reality objectively recorded during the Turing tests of iris recognition. This is why, as separation between the classes of scores, the results obtained by simulating IIV systems (with or without stored digital identities) and presented in Chapter 6 are now the number one among the top iris recognition results obtained on the same test database, at a comfortable distance from what is now considered to be a *'state of the art'* iris recognition result.

Some questions mentioned in **Chapter 7** illustrate the open problems in iris recognition: template aging, consistency and soundness of iris recognition, and iris recognition on non-standard images (recognition in unconstrained acquisition scenarios). They prescribe the limits up to which the thesis can conclude (**Chapter 8**).

The *list of main personal contributions* proposed in this thesis can be found at page 223 as **Apendix 6**.

The *bibliograpy* includes *only* titles cited in the thesis. The articles marked in bibliography with **bold** are our articles. They were written between 2008 and 2011, in direct connection to this thesis.

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BIBLIOGRAPHY

[1] S. Baker, K.W. Bowyer, P.J. Flynn, Empirical Evidence for Correct Iris Match Score Degradation With Increased Time Lapse Between Gallery and Probe Images, Proc. Int. Conf. on Biometrics, pp. 1170-1179, June 2009.

[2] P. Blackburn, M. de Rijke, Y. Venema, *Modal Logic*, Cambridge University Press, 2000.

[3] W.W. Boles, B. Boashash, *A human identification technique using images of the iris and wavelet transform*, IEEE TSP, vol. 46, No. 4, pp. 1185–1188, April 1998.

[4] K.W. Bowyer, K. Hollingsworth, P.J. Flynn, *Image understanding for iris biometrics: a survey*, Computer Vision and Image Understanding, vol. 110, no. 2, pp. 281-307, 2008.

[5] K.W. Bowyer, S.E. Baker, A. Hentz, K. Hollingsworth, T. Peters, P.J. Flynn, *Factors That Degrade the Match Distribution în Iris Biometrics*, Identity în the Information Society, Vol. 2, No. 3, pp. 327-343, December 2009.

[6] K.W. Bowyer, P.J. Flynn, K. Hollingsworth, S. Baker, S. Ring, *Towards the Next Generation of Iris Biometrics Science*, SPIE Newsroom, May 2009.

[7] P.J. Burt, E.H. Adelson, *The Laplacian Pyramid as a Compact Image Code*, IEEE Trans. on Communications, Vol. COM-3l, No. 4, pp. 532-540, April 1983.

[8] W.S. Chen, K.H. Chih, S.W. Shih, C.M. Hsieh, *Personal Identification with Human Iris Recognition based on Wavelet Transform*, MVA2005 IAPR Conference on Machine Vision Applications, May 16-18, pp. 351-354, 2005, Tsukuba Science City, Japan.

[9] J.G. Daugman, *Biometric signature security system*, Harvard University, Cambridge, MA, Tech. Rep., 1990.

[10] J.G. Daugman, *High Confidence personal identification by rapid video analysis of iris, texture*, Proc. IEEE Int. Carnahan Conference on Security Technology, pp. 1-11, 1992.

[11] J.G. Daugman, *High Confidence visual recognition by test of statistical independence*, IEEE TPAMI, vol. 15, pp. 1148-1161, 1993.

[12] J.G. Daugman, *Biometric Personal Identification System Based on Iris Analysis*, United States Patent No. 5`291`560, Mar. 1, 1991/1994, Iri Scan Inc.

[13] J.G. Daugman, *Biometric Decision Landscapes*, Technical Report No. TR482, University of Cambridge, 2000.

[14] J.G. Daugman, C. Downing, *Epigenetic randomness, complexity, and singularity of human iris patterns*, Proceedings of the Royal Society, B, Biological Sciences, Vol. 268, No. 1477, pp 1737-1740, Aug. 2001.

[15] J.G. Daugman, *Demodulation by complex-valued wavelets for stochastic pattern recognition*, Int. Journal of Wavelets, Multi-resolution and Information Processing, Vol. 1, No 1, pp 1-17, 2003.

[16] J.G. Daugman, *The importance of being random: Statistical principles of iris recognition*, Pattern Recognition, Vol. 36, No. 2, pp 279-291, 2003.

[17] J.G. Daugman, *How Iris Recognition Works*, IEEE Transactions on Circuits and Systems for Video Technology, Vol. 14, No. 1, January 2004.

[18] J.G. Daugman, *Probing the uniqueness and randomness of IrisCodes: Results from 200 billion iris pair comparisons*, Proceedings of the IEEE, Vol. 94, No. 11, pp 1927-1935, Nov. 2006.

[19] J.G. Daugman, *New methods în iris recognition*, IEEE Trans. Systems, Man, Cybernetics, B 37(5), pp 1167-1175, Oct. 2007.

[20] L. Flom, A. Safir, *Iris recognition system*, United States Patent No. 4641349 (1985/1987), http://www.patentstorm.us/patents/4641349.html, [22.sept.2008].

[21] D. Gabor, J. London; M. Born, E. Wolf, *Principles of Optics*, 7th Ed., Cambridge University Press, Cambridge, 1999, pp. 557-562.

[22] P. Grother, E. Tabassi, G. Quinn, W. Salamon, *Interagency report 7629: IREX I - Performance of iris recognition algorithms on standard images*, N.I.S.T., October 2009.

[23] J.P. Havlicek, J.W. Havlicek, A.C. Bovik, *The analytic image*, Proc. International Conference on Image Processing, vol.2, pp. 446-449, 1997.

[24] K. Hollingsworth, *Sources of Error în Iris Biometrics*, Thesis (Masters of Science in Computer Science and Engineering, in coordination of K.W. Bowyer and P.J. Flynn), University of Notre Dame, Indiana, April 2008.

[25] K. Hollingsworth, K.W. Bowyer, P.J. Flynn, *Pupil dilation degrades iris biometric performance*, Computer Vision and Image Understanding archive, Vol. 113, No. 1, Elsevier Science Inc., January 2009.

[26] K.P. Hollingsworth, K.W. Bowyer, P.J. Flynn, *The best bits in an iris code*, IEEE TPAMI, Vol. 31, No. 6, pp. 964-973, June 2009.

[27] K. Hollingsworth, K.W. Bowyer, P.J. Flynn, *Similarity of Iris Texture Between Identical Twins*, Proc. 2010 IEEE-CS Conf. on Computer Vision and Pattern Recognition Workshops (CVPRW), pp. 22-29, June 2010.

[28] K. Hollingsworth, K.W. Bowyer, P.J. Flynn, *Image Averaging for Improved Iris Recognition*, Proc. Int. Conf. on Biometrics, pp. 1112-1121, June 2009.

[29] C. Hollitt, *Reduction of computational complexity of Hough transforms using a convolution approach*, Proc. 24th Int. Conf. on Image and Vision Computing, pp. 373, New Zealand, 2009.

[30] *Iris Challenge Evaluation*, N.I.S.T., http://iris.nist.gov/ice/, Cited Mars 2011.

[31] R.G. Johnson, *Can iris patterns be used to identify people*, Los Almos National Laboratory, CA, Chemical and Laser Sciences Division, Rep. LA-12331-PR, 1991.

[32] L.R. Kennell, R.W. Ives, R.M. Gaunt, *Binary Morphology and Local Statistics Applied to Iris Segmentation for Recognition*, Proc. 2006 IEEE Int. Conf. on Image Processing, pp.293-296, Oct. 2006.

[33] F.R. Kschischang, *The Hilbert Transform*, Department of Electrical and Computer Engineering, University of Toronto, http://www.comm.toronto.edu/frank/papers/hilbert.pdf

[34] X. Liu, K.W. Bowyer, P.J. Flynn, *Experiments with an Improved Iris Segmentation Algorithm*, Proc. 4th IEEE Workshop on Automatic Identification Advanced Technologies, pp. 118-123, December 2005.

[35] L. Ma, Y. Wang, T. Tan, *Iris Recognition Based on Multichannel Gabor Filtering*, 5th Asian Conference on Computer Vision, 23-25 January 2002, Melbourne, Australia.

[36] L. Ma, Y. Wang, T. Tan, *Iris Recognition Using Circular Symmetric Filters*, Proc. 16th Int. Conf. on Pattern Recognition, Vol. 2, pp. 414-417, December 2002.

[37] L. Ma, T. Tan, Y. Wang, D. Zhang, *Personal Identification Based on Iris Texture Analysis*, IEEE TPAMI, Vol. 25, No. 12, pp. 1519-1533, 2003.

[38] L. Ma, T. Tan, Y. Wang, D. Zhang, *Efficient Iris Recognition by Characterizing Key Local Variations*, IEEE TIP, Vol. 13, No. 6, June 2004.

[39] L. Masek, *Recognition of Human Iris Patterns for Biometric Identification*, University of Western Australia, 2003.

[40] J. De Mira, J. Mayer Jr., *Image Feature Extraction for application of Biometric Identification of Iris - A Morphological Approach*, Proc. 16th Brazilian Symposium on Computer Graphics and Image Processing, pp.: 391-398, 2003.

[41] D.M. Monro, S. Rakshit, D. Zhang, *DCT-Based Iris Recognition*, IEEE TPAMI, Vol.29, No.4, pp. 586-595, 2007.

[42] W. Pegden, *Sets resilient to erosion*, Department of Mathematics, Rutgers University, http://people.cs.uchicago.edu/~wes/erosion.pdf, September 2009.

[43] P.J. Phillips, W.T. Scruggs, A.J. O'Toole, P.J. Flynn, K.W. Bowyer, C.L. Schott, M. Sharpe, *FRVT 2006 and ICE 2006 Large-Scale Results*, NIST, http://iris.nist.gov/ice/FRVT2006andICE2006LargeScaleReport.pdf, 2007.

[44] **N. Popescu-Bodorin**, L. State, *Optimal luminance-chrominance downsampling through Fast k-Means Quantization*, Proc. 3rd Annual South East European Doctoral Student Conference, vol. 2, pp. 111-125, SEERC, Thessaloniki, 2008.

[45] **N. Popescu-Bodorin**, *Fast k-Means Image Quantization Algorithm and its Application to Iris Segmentation*", Scientific Bulletin, University of Pitesti, No. 14, pp. 159-176, 2008.

[46] **N. Popescu-Bodorin**, *Exploring New Directions în Iris Recognition*, Proc. 11th International Symposium on Symbolic and Numeric Algorithms for Scientific Computing, pp. 384-391, Conference Publishing Services, IEEE Computer Society, Sept. 2009.

[47] **N. Popescu-Bodorin**, *A Fuzzy View on k-Means Based Signal Quantization with Application în Iris Segmentation*, 17th Telecommunications Forum, IEEE Serbia & Montenegro COM Chapter and Section, University of Belgrade, 24-26 November 2009, Belgrade, SERBIA.

[48] **N. Popescu-Bodorin**, L. State, *Cognitive Binary Logic - The Natural Unified Formal Theory of Propositional Binary Logic*, Recent Advances în Computational Intelligence, pp. 135-142, WSEAS Press, April 2010.

[49] **N. Popescu-Bodorin**, *'Fragile Bits' vs. Multi-Enrollment - A Case Study of Iris Recognition on Bath University Iris Database*, ROMAI Journal, No.5, Vol. 2, pp. 127-144, October 2009.

[50] **N. Popescu-Bodorin**, *Automatic Detection of Common Long-Term Monetary Policies on Global Exchange Market Using Gabor Analytic Phase Binary Encoder*, Analele Universității Ovidius, Economic Sciences Series, Volume X, No. 1, p. 776-780, 2010.

[51] **N. Popescu-Bodorin**, V.E. Balas, *AI Challenges în Iris Recognition. Processing Tools for Bath Iris Image Database*, Recent Advances în Automation & Information, Proc. 11th Int. Conf. on Automation & Information, pp. 116-121, WSEAS Press, June 2010.

[52] **N. Popescu-Bodorin**, *Processing Toolbox for the University of Bath Iris Image Database*, Matlab demo program, http://fmi.spiruharet.ro/bodorin/pt-ubiid/

[53] **N. Popescu-Bodorin**, V.E. Balas, *Comparing Haar-Hilbert and Log-Gabor based iris encoders on Bath Iris Image Database*, Proc. 4th International Workshop on Soft Computing Applications, pp. 191-196, IEEE Press, July 2010.

[54] **N. Popescu-Bodorin**, V.E. Balas, *From Cognitive Binary Logic to Cognitive Intelligent Agents*, Proc. 14th Int. Conf. on Intelligent Engineering Systems, pp. 337-340, Conference Publishing Services, IEEE Computer Society, May 2010.

[55] **N. Popescu-Bodorin**, V.E. Balas, *Learning Iris Biometric Digital Identities for Secure Authentication. A Neural-Evolutionary Perspective Pioneering Intelligent Iris Identification*, chapter book, Recent Advances în Intelligent Engineering Systems, Springer Verlag, in press 2011.

[56] **N. Popescu-Bodorin**, V.E. Balas, *Exploratory Simulation of an Intelligent Iris Verifier Distributed System*, Proc. 6th IEEE International Symposium on Applied Computational Intelligence and Informatics, pp. 259-262, IEEE Press, June 2011.

[57] **N. Popescu-Bodorin**, V.E. Balas, I.M. Motoc, *8-Valent Fuzzy Logic for Iris Recognition and Biometry*, accepted in the 5th Int. Conf. on Computational Intelligence and Intelligent Informatics, September 15-17, Floriana, Malta, 2011.

[58] **N. Popescu-Bodorin**, V.E. Balas, I.M. Motoc, *Iris Codes Classification Using Discriminant and Witness Directions*, accepted in the 5th Int. Conf. on Computational Intelligence and Intelligent Informatics, September 15-17, Floriana, Malta, 2011.

[59] S. Rakshit, D.M. Monro, *Effects of Sampling and Compression on Human IRIS Verification*, Proc. 2006 Int. Conf. on Acoustics, Speech and Signal Processing, Toulouse, 14-19 May 2006.

[60] S. Rakshit and D.M. Monro, *Pupil Shape Description Using Fourier Series*, Workshop on Signal Processing Applications for Public Security and Forensics (IEEE SPS - SAFE 2007), April 2007.

[61] S. Rakshit, D.M. Monro, *Robust Iris Feature Extraction and Matching*, Proc. IEEE Int. Conf. on Digital Signal Processing, pp. 487-490, Cardiff, 1-4 July 2007.

[62] T.J. Ross, *Fuzzy logic with engineering applications*, John Wiley & Sons, 2004.

[63] D. Salomon, *Data compression: the complete reference*, Springer-Verlag, New York, NY, 2006.

[64] D. Schonberg, D. Kirovski, *Iris compression for cryptographically secure person identification*, Proc. 2004 Data Compression Conference, pp. 459, August 2004.

[65] D. Schonberg, D. Kirovski, *EyeCerts*, IEEE Trans. on Information Forensics and Security, Vol. 1, No. 2, pp. 144-153, June 2006.

[66] M. Sugeno, T. Yasukawa, *A Fuzzy-Logic-Based Approach to Qualitative Modeling*, IEEE Trans. on Fuzzy Systems, Vol. 1, No. 1, February 1993.

[67] C.H. Sulochana, S. Selvan, *Iris recognition based on contourlet transform and dominant energy features*, Advanced Modeling and Optimization, Vol. 9, No. 2, 2007.

[68] Z. Sun, Y. Wang, T. Tan, J. Cui, *Improving Iris Recognition Accuracy Via Cascaded Classifiers*, IEEE Trans. on Systems, Man, and Cybernetics, vol. 35, no. 3, pp. 435-441, August 2005.

[69] T. Tan, L. Ma, *Iris Recognition: Recent Progress and Remaining Challenges*, Proc. of SPIE, Vol. 5404, pp. 183-194, Apr. 2004.

[70] C. Tisee, L. Martin, L. Torres, M. Robert, *Person identification technique using human iris recognition*, Proc. 15th Int. Conf. on Vision Interface, Canadian Image Processing and Pattern Recognition Society, May 2002, url retrived on September 2009: http://www.cipprs.org/vi2002/pdf/s6-1.pdf .

[71] A.M. Turing, *Computing machinery and intelligence*, Mind, 59, pp. 433-460, 1950.

[72] University of Bath Iris Image Database (retrived on September 2009), http://www.bath.ac.uk/elec-eng/research/sipg/irisweb/

[73] J. Vartiainen, *Iris Recognition Systems and methods*, Lappeenranta University of Technology, Department of Information Technology, retrived on 02.Febr.2008 from

www.it.lut.fi/kurssit/03-04/010970000/seminars/Vartiainen.pdf

[74] R.P. Wildes, J.C. Asmuth, G.L. Green, S.C. Hsu, R.J. Kolzynski, J.R. Matey, S.E. McBride, *Iris recognition for security access control: Final Report*, National Information Display Laboratory, Princeton, NJ, Tech. Rep., 1992.

[75] R.P. Wildes, J.C. Asmuth, G.L. Green, S.C. Hsu, R.J. Kolzynski, J.R. Matey, S.E. McBride, *A system for automated iris recognition*, Proc. IEEE Workshop on Applications of Computer Vision, Sarasota FL, pp. 121-128, 1994.

[76] R.P. Wildes, J.C. Asmuth, K.J. Hanna, S.C. Hsu, R.J. Kolczynski, J.R. Matey, S.E. McBride, *Automated non-invasive iris recognition system and method*, United States Patent No. 5`572`596 (1994/1996), Nov. 5, 1996, David Sarnoff Research Center Inc.

[77] R.P. Wildes, J.C. Asmuth, G.L. Green, S.C. Hsu, R.J. Kolzynski, J.R. Matey, S.E. McBride, *A machine vision system for iris recognition*, Machine Vision Applications, vol. 9, pp. 1-8, 1996.

[78] R.P. Wildes, *Iris Recognition - An Emerging Biometric Technology*, Proceedings of the IEEE, Vol. 85, No. 9, September 1997.

[79] N. Yager, T. Dunstone, *The Biometric Menagerie*, IEEE TPAMI, vol. 32, no.2, pp. 220-230, Feb. 2010.

[80] S. Yang, I. Verbauwhede, *Secure Iris Verification*, Proc. IEEE Int. Conf. on Acoustics, Speech and Signal Processing, vol. II, pp. 133-136, April 2007.

[81] S. Yoon, S.S. Choi, S.H. Cha, Y. Lee, C.C. Tappert, *On the Individuality of the Iris Biometric*, Proc. Int. Conf. on Image Analysis and Recognition, Vol. 3656, No. 2, pp. 1118-1124, Toronto ON, CANADA, 2005.

[82] L.A. Zadeh, *Outline of a new approach to the analysis of complex systems and decision processes*, IEEE Trans. Syst., Man, Cybern., vol. 3, pp. 28-44, 1973.

[83] L.A. Zadeh, *Precisiation of meaning via translation into PRUF*, Cognitive Constraints on Communication, L. Vaina and J. Hintikka, (eds.), pp. 373-402. Dordrecht: Reidel, 1984.

[84] L.A. Zadeh, *Fuzzy logic: a new look*, Fuzzy Logic and Intelligent Technologies in Nuclear Science, 8th Int. Conf. on Computational Intelligence in Decision and Control, Madrid, Spain, September 21-24, 2008.

[85] L.A. Zadeh, *Toward extended fuzzy logic – A first step*, Fuzzy Sets and Systems, 160(2009), pp. 3175-3181, 2009.

[86] L.A. Zadeh, *Toward Human Level Machine Intelligence - Is It Achievable? The Need for a Paradigm Shift*, International Journal of Advanced Intelligence, Vol. 1, No 1, pp. 1-26, November, 2009.

[87] Y. Zhu, T. Tan, Y. Wang, *Biometric personal identification based on iris patterns*, Proc. 15th Int. Conf. on Pattern Recognition, Vol. 2, pp. 801-804, 3-7 Sept 2000.

[88] S. Ziauddin, M.N. Dailey, *Iris recognition performance enhancement using Weighted Majority Voting*, Proc. IEEE Int. Conf. on Image Processing, pp. 277-280, 2008.

[89] J. Zuo, N.A. Schmid, *A Model Based, Anatomy Based Method for Synthesizing Iris Images*, Proc. of Int. Conf. on Biometrics, vol. 3832, pp. 428-435, Hong Kong, CHINA, 2006.

[90] J. Zuo, N.A. Schmid, X. Chen, *On Generation and Analysis of Synthetic Iris Images*, IEEE Trans. on Information Forensics and Security, Vol. 2, No. 1, pp. 77-90, 2007.