VLSI Design, 2002 Vol. 14 (1), pp. 1–3

Spectral Techniques and Decision Diagrams—Guest Editorial

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(Received 20 January 2000; In final form 10 April 2000)

This special issue of the *VLSI DESIGN: an International Journal of Custom-Chip Design, Simulation and Testing* is devoted to spectral techniques, new types of decision trees and diagrams, their applications, efficient ways of their calculation and mutual relations between spectral techniques and classical decision diagrams.

Manipulations and calculations with discrete functions are fundamental tasks in many areas of Computer Science and Engineering. Many problems in digital system design, simulation and testing can be expressed as a sequence of operations on discrete functions. The performance of Computer-Aided Design systems used in solving various problems in this area strongly depends on the efficiency of representations of discrete functions. Decision Diagrams (DDs) have proved very convenient data structure for discrete function representations, permitting manipulations and calculations with large functions efficiently in terms of time and space. In many applications, as for example those involving large matrices, conventional algorithms are significantly improved by using DDs. In logic design, such applications relate to basic problems of the design, verification, simulation and testing logical networks. Besides Boolean functions, some other types of discrete representations, such as multi-valued functions, cube sets, EXOR-based spectral and probabilistic formulas have to be dealt with. Hence the numbers of different decision trees and diagrams have been introduced for these various applications and representations.

The spectral or polynomial representation of Boolean function is obtained by expressing it in terms of an orthogonal basis. The most popular basis is formed by discrete Walsh functions. Note that the spectral and the polynomial representation of a Boolean function are equivalent. The discrete orthogonal functions are referred to as the basis functions when the spectral or abstract harmonic terminology is used and as monomials when the polynomial terminology is used. Such polynomial representations have extensive applications in coding theory and cryptography as well as design of nonlinear filters. Spectral techniques based on Walsh, Haar, Arithmetic and Reed–Muller transforms have been used in digital logic design for more than 30 years. These techniques have been used for Boolean function classification, disjoint decomposition, identification of symmetries, parallel and serial linear decomposition, spectral translation synthesis (extraction of linear pre- and post-filters), multiplexer synthesis, threshold logic synthesis, state assignment and testing, and evaluation of logic complexity. The renewed interest in applications of spectral methods in design of VLSI digital circuits is caused by their excellent design for testability properties and in their efficiency in Boolean mapping problems. Furthermore, the practical applicability of these techniques was greatly improved with the development of efficient methods that allow calculating and operating on spectra of Boolean functions directly from reduced representations of such functions in the form of arrays of cubes or decision diagrams. Following from these recent developments, techniques have been presented for efficient spectral translation to decompose a circuit into a cascade of two sub circuits: linear block composed of EXOR gates fed by the primary input of the overall circuit. Such linear decomposition drastically simplifies the synthesis task. The choice of suitable linear transformation is based on a complexity measure assigned to each Boolean function that is heuristically related to the complexity of the final circuit implementation. To avoid the experimental costs of computing the Walsh transform, Binary Decision Diagrams (BDDs) based techniques are used. Recently the idea of linear transformations is applied to decision diagrams. By combining powerful spectral linear techniques with variable reordering techniques, it is possible to synthesize large Boolean functions with standard Computer-Aided Design tools that fail otherwise.

The areas addressed by this special issue span spectral transforms, their applications and efficient calculation methods through decision diagrams. New spectral decision diagrams are also emerging that support larger data structures allowing more complex discrete representations to be implemented that was previously impossible.

ISSN 1065-514X print/ISSN 1563-5171 online
DOI: 10.1080/10655140290009756

The first paper "Spectral Transforms Calculation through Decision Diagrams" authored by R.S. Stankovic and B.J. Falkowski is a general introduction to the whole special issue. It shows the calculation of spectral transforms through DDs and relationship of this method with Fast Fourier Transform (FFT) algorithm. It is shown that the basic operations in FFT are performed not on vectors, but instead on parts of DDs as a data structure. Such data structure represents the input data, the intermediate data as well as the final results. Throughout this paper all the examples for spectral transforms calculation are based on recently introduced Complex Hadamard transform.

The second paper "Generalized Inclusive Forms—New Canonical Reed–Muller Forms Including Minimum ESOPs" by M. Chrzanowska-Jeske, A. Mishchenko and M. Perkowski discusses new forms to represent logic functions by using EXOR operators. This paper describes two families of canonical Reed–Muller forms called Inclusive Forms and Generalized Inclusive Forms that include minimum Exclusive-Sum-Of-Products (ESOPs) for an arbitrary Boolean function. A new type of special binary tree, which underlies Inclusive Forms and permits their enumeration, is also discussed. Set theoretical relationship between families of EXOR canonical forms is also presented. The paper also shows computer results indicating that Generalized Inclusive Forms reduce significantly the search space for minimum ESOP by several orders of magnitude and this reduction grows exponentially with the increase of number of variables.

The next paper "Circuit Synthesis from Fibonacci Decision Diagrams" by R.S. Stankovic, M. Stankovic, J. Astola and K. Egiazarian introduces a new type of decision diagrams called Fibonacci Decision Diagrams (FibDDs) and their applications in circuit synthesis. FibDDs are a data structure for efficient representation in terms of space and time for such discrete functions defined in a set of points whose cardinality is equal to a generalized Fibonacci numbers. The known methods of circuit synthesis directly from DD of some discrete function into a network realizing this function are extended to FibDDs. The method using reachability matrices provided an efficient approach for factorization of Fibonacci expressions assigned to FibDDs. Hence, in this paper known DDs based methods for circuit synthesis have been completely generalized and transferred to Fibonacci interconnection topologies.

The next paper "Efficient Algorithms for Creation of Linearly-Independent Decision Diagrams and Their Mapping to Regular Layouts" by M. Perkowski, B.J. Falkowski, M. Chrzanowska-Jeske and R. Drechsler introduces a new type of DDs. These diagrams, being new forms to represent logic functions by using AND/OR/EXOR bases, are called Linearly Independent Decision Diagrams (LIDDs). Since their nodes are based on all possible nonsingular expansions for a pair of variables there are 840 different types of nodes in the tree. The number of nodes in LIDDs is usually much smaller than 1/3 of the number of nodes in Kronecker diagrams. The LIDDs can be used in synthesis of multilevel AND/OR/EXOR circuits with regular structures as well as to optimize Linearly Independent Programmable Logic Arrays (LIPLAs). New efficient synthesis algorithms using LIDDs are also discussed.

The next paper "Logic Circuit Equivalence Checking Using Haar Spectral Coefficients and Partial BDDs" by M.A.Thornton, R. Drechsler and W. Gunther uses partial Haar Spectral Diagrams (HSDs) for probabilistic logic circuit equivalence checking. Partial HSDs are used to represent a subset of Haar spectral coefficients for two Boolean functions whose equivalence is being checked. The resulting coefficients are later used to compute and refine through iterations the probability that two functions are equivalent. This method is applicable for cases when two verified functions need a lot of memory for complete BDD representations. Experimental results for the presented approach are included in the paper.

The next paper "Foundations for Applications of Gibbs Derivatives in Logic Design and VLSI" by R.S. Stankovic, M. Stankovic and R. Creutzburg discusses applications of Gibbs derivatives in logic design. Standard logic derivatives related to Reed–Muller and Arithmetic transforms are frequently used in fault detection, functional decomposition, detection of various types of symmetries etc. Gibbs derivatives are a broad family of differential operators on groups that have different properties that logic derivative. By using the characterization of Gibbs derivatives through Fourier coefficients, efficient method of calculating Gibbs derivatives through DDs is described.

The next paper "Spectral Testing of Digital Circuits" by B.J. Falkowski gives a review of the use of Walsh spectral coefficients in the area of testing of digital circuits. In the first part of the paper, the links between spectral techniques and classical logic terms are discussed. As spectral coefficient testing is generalization of syndrome testing, these two methods are discussed in the paper. The problem of constructing optimal data compression schemes by spectral techniques is also discussed. The last approach is very useful for compressing test responses of logical networks and PLAs.

The last paper of the special issue is "Term Trees in Application to an Effective and Efficient ATPG for AND–EXOR and AND–OR Circuits" by L. Jozwiak, A. Slusarczyk and M. Perkowski. New types of DDs called Term Trees (TTs) are introduced. TTs are very convenient data structure for AND–OR and AND–EXOR circuits and their application in structural automatic test-pattern generation (ATPG) is shown. The experimental results indicate that for many benchmark functions TTs are a compact data structure allowing fast manipulation.

In conclusion, the above commissioned papers in this special issue are intended to cover the most important issues, new data structures and future possible applications of spectral techniques and decision diagrams in many areas of Computer Science and Engineering. The editor is

most grateful to the authors of the papers cited above for their will to contribute their papers to the special issue. I hope that you enjoy this special issue. I believe that the collection of articles assembled here provides a good insight into the potential and current status what spectral techniques and decision diagrams have to offer. I also hope that these articles with so many novel ideas will encourage you to further explore topics in the area of spectral techniques and decision diagrams.

Finally, I would also like to thank those anonymous reviewers who provided valuable comments to the authors. Last but not least, I would like also to thank Professor George W. Zobrist, the Editor-in-Chief of *VLSI Design* for his support of this special issue.

Author's Biography

Bogdan J. Falkowski received the MSEE degree from Technical University of Warsaw, Poland and the PhD degree in Electrical and Computer Engineering from Portland State University, Oregon, USA. His industrial experience includes research and development positions at several companies. He then joined the Electrical and Computer Engineering Department at Portland State University. Since 1992, he has been with the School of Electrical and Electronic Engineering, Nanyang Technological University in Singapore where he is currently an Associate Professor. His research interests include VLSI systems and design, switching circuits, testing, and design of algorithms. He specializes in the design of digital circuits with the use of spectral methods and has published 3 book chapters and over 150 refereed journal and conference articles in this area. He is a senior member of the IEEE, member of international advisory committee for International Conference on Applications of Computer Systems and technical chair for IEEE International conference on Information, Communication and Signal Processing held in December 1999 in Singapore.